A PRACTICAL TREATISE ON THE MOVEMENT OF SLIDE VALVES BY ECCENTRICS.

FOR THE USE OF

ENGINEERS, DRAUGHTSMEN, MACHINISTS, AND STUDENTS IN GENERAL.

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PREFATORY REMARKS.

The action of the slide valve of the steam engine, operated through various intervening devices by a motion derived from an eccentric, has been so often and so ably discussed, that in presenting a new treatise on the subject, an explanation seems called for, offering an excuse for its appearance. The object of the present work is that of aiding practical engineers in forming a clear idea of, first, the nature of the motion, and what the valve *can* be made to do; second, the requirements of the engine, and what the valve *must* be made to do; and, third, the construction of the movement, and how to make the valve do what it is to do. And the plea for its existence, upon which main reliance is placed, rests primarily on the manner in which these questions are presented.

Much labor and zeal have been expended, not to say wasted, in treating this matter analytically—the method being to embody the elements, constant and variable, of the whole combination, including all the connecting rods, cranks, eccentrics, rock shafts, links, and levers, making up the working gear interposed between the piston and the valve, in an equation expressing the movement as influenced by them all; and by discussing this equation to deduce results as affected by various supposed changes in the proportions or relations of these elements.

The subject affords a good field for the display of analytical acumen; and this method of employing algebraic skill for a practical purpose is at once elegant and refined; but such investigations do not answer the purposes above set forth; admirable as they may be intrinsically, they are so mainly to the select few as interesting studies of applied mathematics.

It must be borne in mind that of those who study closely the mechanical movements of the steam engine, particularly those who are directly interested in the practical matter of engine building—the draughtsmen who design as well as the mechanics who execute—the great majority are not versed in the higher mathematical branches. And more especially is it true that they are seldom of the order of mind which turns naturally to analysis as a mode of solving problems ; the *geometrical* reasoners are the ones most likely to adopt a profession in which graphic methods are in constant use, and to many, proficient in these, any thing written in the language of symbols is a sealed book, while to many more it is a very dry one.

Again, the connection between an abstract formula and its concrete embodiment is so indirect and obscure, that even those competent to trace the equation through its various transformations from the initial to the final stage, have frequent need to resort to graphic means of illustrating their progress, and are absolutely driven back to them in order to construct their ultimate expressions, and reduce their theoretical deductions to a practical form.

It is to be considered, too, that the engine itself is not a creature of analytical instincts ; its parts move with geometrical precision, in lines and about centres which, having fixed linear relations to each other, are just as susceptible of accurate delineation on paper as of accurate adjustment in metal ; they did so before their motions were analyzed, and would continue to do so to the end of time, though the art of analysis were forgotten. In fact, the mathematical education of the engine has never gone beyond geometry ; it was planned by geometry, it was built by geometry, and it runs by geometry. To be sure, you may examine it analytically, and formulate the results ; but, algebra or no algebra, it will answer no questions which it cannot answer by geometry.

Since, then, the valve movements must eventually be constructed by graphic processes, whether they be previously discussed analytically or not, there seems to be no good reason why the former method should not be separately used in the whole investigation.

On the contrary, it would appear from the preceding considerations that it is peculiarly adapted, not only to the elucidation of this subject, but to the tastes of those specially addressed; it has, therefore, been adopted, to the entire exclusion of algebraic analysis, which those who prefer it may find exhaustively used in other works.

In regard to the general arrangement and subdivision of the matter presented, it is proper to remark that, in the author's opinion, the chief source of the difficulty often found in imparting, even by the graphic method, a thorough insight into the action of the slide valve, and the construction of its movement, is to be found in the fact that usually the investigation starts out with the three-ported or common slide, very often miscalled "the simplest form of the valve;" and introduces at once the several adjuncts of "lap," "lead," "inside clearance," etc., which, though simple enough when separately considered, are bewildering to the beginner when he is at once confronted with them all.

By dissecting this valve, and considering its members and their functions one by one, the author has endeavored to make their combined action more readily comprehended.

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CHAPTER I.

GENERAL INVESTIGATION OF THE "ECCENTRIC MOTION."

1. The slide valve of the steam engine, as the name implies, is a valve which controls the passage of the steam into or out of the cylinder, or both, by a reciprocating motion upon a surface provided with suitable openings, to which the valve is accurately fitted.

The form of this surface may be varied ; the valve may be made as a piston, working in a cylinder, in which case it is called a piston valve ; or it may have a rotatory reciprocation, being in the form of a portion of a cylinder, and more or less closely resembling a cock, or plug valve.

These, however, are variations of form, and of form only ; the general principles of construction, and the mode of action, are identical with those of the more common arrangement, in which the valve is of a rectangular figure, and slides to and fro in a right line upon a plane surface.

2. It is self-evident, that there is no necessary connection between such a valve and an eccentric ; like any other valve, it may receive the requisite motion through the intervention of devices limited in number and in variety of detail only by the ingenuity of the contriver. But the most simple and obvious of these, in many respects and for many purposes the best, and the one by far the most commonly used, is that of the eccentric. It is with this that we have to do ; in what follows, therefore, it is our object to explain, step by step, the construction and operation of the slide valve thus actuated.

3. The word construction, it should be borne in mind, is used in a technical sense, including not merely the abstract definition of the form and dimensions of any given part, but the processes by which these are determined and arranged in due relation to other parts ; it means not a bare statement

that a thing *is* so, but in addition the reasons why it must be so, and the ways and means of making it so.

These demonstrations and processes, as stated in the introduction, are geometrical; so that by the *construction* of a movement or of any portion of the combinations which may be discussed, is meant the mechanical delineation of whatever may be necessary to arriving at the required result.

If it be stated by way of objection, that the accuracy of the result depends upon that of the diagrams, it will suffice to say, that this in no wise affects the positive nature of the reasoning; and that, since the draughtsman who constructs can be, and of right ought to be, as accurate as the mechanic who executes, this method gives, in a clear and ready way, results both practically and theoretically correct. And, if greater nicety be insisted on by those of an analytical turn of mind, the resources of trigonometry are at all times available to verify the measurements.

4. Assuming, then, to start with, that the valve is to be moved backward and forward in a right line by means of an eccentric, the first thing to be considered is the nature of the motion thus imparted. But before entering upon this, it may be remarked that, as illustrated by Figs. 1 and 2, an eccentric is only a crank with an exaggerated crank-pin. An apology would be needed for mentioning this identity, were it not that the author has found prevalent, even among those whose practical familiarity with these things should have taught them better, a misty notion that in some mysterious way a big eccentric has the property of imparting a smoother and more equable movement than a little crank; a delusion which will be at once dispelled by a comparison of these figures.

This being so, a crank of the ordinary form may be, and frequently is, used instead of an eccentric—in point of fact, the latter is the real substitute, being a mechanical equivalent introduced because the use of the former is for special reasons inconvenient or impracticable.

5. And in Fig. 3 is shown the simplest arrangement of an engine with a slide valve thus actuated; the eccentric (or its equivalent crank) being

fixed on a shaft turned by the "main crank," which is moved by a connecting rod jointed to the end of the piston rod ; a smaller connecting rod in like manner conveying to the valve-stem the motion of the eccentric. It will be shown hereafter that the motion thus given to the valve is such as to meet the requirements of the engine ; assuming that to be true, a consideration of this figure will show that it is precisely similar to that of the piston. And, since the shaft to which the eccentric is fixed, here makes a half revolution while the piston makes one stroke, it follows that whatever device may be used for converting the reciprocating motion of the piston into rotatory motion—or even if it be not thus converted at all, the slide valve may be actuated by an eccentric fixed on any shaft which makes a half revolution at each stroke of the piston.

6. The angular position of the eccentric rod in Fig. 3 also calls attention to two features of the crank motion, which are more clearly illustrated by the diagram, Fig. 4. One is, that a portion of the power is expended in side pressure upon the piston rod or valve-stem, of which the motion is rectilinear ; the other, that although a half revolution of the crank produces a full stroke of the part to which its motion is transmitted, yet one quarter of a revolution causes a little more, and the other quarter a little less, than one-half of the stroke to be performed. With the first difficulty we have nothing to do ; but the second introduces an irregularity into the movement, of which it will be well to get rid.

7. Both these troubles will diminish as the length of the connecting rod is increased, and vanish when it becomes infinite ; and it will be much more simple at first to disregard entirely the details of the actuating gear, and suppose both the main connecting rod and the eccentric rod to be infinitely long. This supposition may be readily realized by means of the device shown in Fig. 5, which, under the name of the "slotted cross-head connection," is sometimes employed in practice. No connecting rod, properly so called, is used ; but to the piston rod is secured a cross-head, provided with a slot equal in breadth to the diameter of the crank-pin, which moves freely in it.

Thus, the transverse motion of the crank-pin being accommodated by the slot, the piston rod will traverse exactly as required by the longitudinal motion. The relative motions of the parts are therefore precisely such as would result from the use of a connecting rod of infinite length; a similar attachment to the valve-stem, as shown in the figure, secures the same desideratum in regard to the relative movements of the valve-stem and the eccentric or its equivalent crank.

8. The nature of this arrangement being understood, we will, before considering the operation of the valve in connection with the engine, inquire into the particulars of the movement thus derived from the eccentric, and ascertain the precise nature and limitations of the control which the valve exercises over the port. As the length of the valve-stem has nothing to do with its motion, we have, in some of the following figures, shown a slotted piece attached directly to the back of the valve, with the pin of the eccentric crank working in it; thus bringing the whole action directly under the eye, and more clearly illustrating the relations between the different parts. In Fig. 6 is shown a port *c d*, covered by a valve *a b*, which is moved, in the manner just described, by a crank of given length. The centre of the crank-pin describes a circle about the centre *o* of the shaft; and if a line L M be drawn through *o*, parallel to the direction in which the valve slides, it will evidently divide the circle equally in such a manner that the crank will move the valve in one direction while describing one half, and in the opposite direction while describing the other half. This line L M is called the line of motion.

9. The whole travel of the valve is, therefore, equal to the diameter *e f*; and if when the crank is at *e*, the extreme limit of motion in the direction L M, the edge *a* of the valve be placed flush with the edge *c* of the port, as shown in the figure, it is obvious at a glance that, no matter in which direction the crank revolves, the port will be opened instantly, and will continue to open until the crank reaches *f*, when the edge *a* of the valve will be at a'; after that, the valve will return, and close the port. Both the valve and the port, then, as here made, are of superfluous breadth; their edges

b and d may be moved to the right as far as a', when, the breadth of each being equal to the travel, we shall have at once the widest port that the valve can open, and the narrowest valve that can close it.

But as the port under such circumstances will only be covered at the instant when the crank is at e, this arrangement can be of no practical use ; and the figure is introduced merely to show the nature of the motion, and the extreme limits of what can be effected by it with a given travel.

10. A valve in accordance with these limits is shown in Fig. 7 ; and regarding this, we recapitulate these features of its action, viz.: that the port is fully opened, and is just closed, once during each revolution ; that it is opened from one side by a motion of the valve in one direction, and that it is closed on the same side, by the return of the valve in the other direction. These features, it will be hereafter seen, are precisely those which characterize the action of "the *main slide valve*," commonly so called in contradistinction to what are known as "independent" cut-off or exhaust valves, which are also frequently made in the form of slide valves, and operated by eccentrics. Since the former is the first which will be considered in connection with the engine, it is proper to inquire in what manner, to what extent, and with what effects, the elements of this combination can be varied under the conditions above specified, before considering modifications in which these conditions are not observed.

11. Keeping these conditions in view, then, it is clear that when the crank is in the position shown in the figure, the relative positions of the edges a and d cannot be changed ; if we extend the valve by moving a to the right, that edge cannot move far enough to the left to coincide with d, and the port will not be fully opened ; if, on the other hand, we diminish the port by moving d to the right, a will move past it to the left, and thus a part of the travel will be wasted. We may extend the valve by moving b to the left, as far as we please ; but (as we see from Fig. 6) it will do no good, if carried beyond the small extent which might in practice be allowed in order

to make sure of a tight joint when the valve is in the position here represented.

12. Hence, no extension of the port or reduction of the valve in either direction being admissible, and the extension of the valve being useless, the only change that can be made in the whole combination is a reduction of the port by moving the edge *c* to the left. This new state of things is illustrated in Fig. 8, the other parts having the same relative position as in the preceding figures. The valve must now move through a space equal to the diminution in the breadth of the port, before the latter will be opened at all; and, erecting at *c* a perpendicular *c l*, it will cut the circle at two points *g*,*h*, equidistant from *e*; and since the supplemental arcs *h f*, *g f*, are equal to each other, the action will in this case also be the same, no matter in which direction the crank revolves. The valve acts to open the port while the crank is passing through the arc *h f*, or *g f*, as the case may be, and to close it, while the crank describes the adjacent equal arc on the other side of the line L M, and the port remains closed while it passes through the arc *h g*.

13. Under the above conditions, then, we can vary the original combination shown in Fig. 7 only in this way: we may reduce the port as much as we please by moving the edge *c* farther and farther to the left; but however narrow we make the port, we cannot make the breadth of the valve less than the travel *e f*. If we cut anything off the edge *a* it will move past *d* to the *left*, thus wasting a part of the travel; and if we cut anything off the edge *b* it will move past *d* to the *right*, thus opening the port twice during the revolution.

14. It will be shown subsequently that if this happens, the valve will no longer be fitted to perform the functions of either a steam or an exhaust valve, controlling ports which lead directly into the cylinder. But there is a form of independent cut-off valve, admitting steam into a chest, whence its entrance into the cylinder is regulated by the main slide; and the port of such a valve *must* be opened twice during each revolution of the eccentric;

so that it is proper now to examine the effects upon the action, arising from the last-mentioned modification, of cutting off the edge b, of the valve.

In Fig. 9 is shown a valve thus diminished in breadth, the parts retaining the same relative positions as before.

It is plain from an examination of this figure, that since a will as before coincide with d at the end of a half revolution, the port will, as in the previous arrangement, be just fully opened from the side c; and that in order to have it just fully opened from the other side d, we must move the edge b of the valve to the right, as we have done, until it coincides with c when the crank is at e; in other words, we must cut off from the valve a piece as wide as the port. And further: since the valve must be as wide as the port in order to cover it, the latter cannot in this case be wider than half the travel, which is its breadth in the figure. Thus we have the extreme limit of what can be done with this arrangement; the port will be closed only at the instants when the crank is vertical, and by a motion of the crank in either direction it will be opened on one side or the other.

15. As it stands, therefore, this would be of no more use than the valve shown in Fig. 7; and since, as just remarked, we cannot make the port wider and the valve narrower, the only possible modification is to do the other thing; that is, to make the valve wider and the port narrower, by moving the edges b, c, to the left.

We have in Fig. 10 a representation of this valve thus modified, with the relative positions of the parts still unchanged. Erecting, as in Fig. 8, the perpendicular $c\,l$, we have the chord, $g\,h$, bisected at i. Make $oi' = oi$, draw through i' the chord $g'h'$ equal and parallel to $g\,h$, and join $g\,h'$, $h\,g'$; we have then a diagram which enables us readily to trace the action of the valve.

As before, the direction of the revolution makes no difference; supposing it to correspond with that of the clock, we see that when the crank reaches h', the edge b will have reached d, closing the port on that side; it will remain closed while the crank moves from h' to h, when the edge a, having reached c, will begin to open it from that direction—and at the end of

the half revolution, a having gone to d, the valve will again be full open, as it now is. The upper half of the circle being divided precisely like the lower half, the port will be closed and opened in a similar manner during the return of the valve.

16. But there is another way in which a valve may be made to open and close the port twice during each revolution; that is, by making an opening in the valve as well as a port in the valve-seat, so that the latter will be opened and closed by the passage over it of this opening.

This arrangement is depicted in Fig. 11, and its mode of action is sufficiently obvious. As in Fig. 9, the breadth of the ports, in both the valve and the valve-seat, is equal to half the travel; and a moment's reflection will show that it can be no greater; since if it were, the edge a would no longer be able to move back to d, as it must do in order to close the port; so that the figure illustrates the extreme limit in this case also, and, as before, the only admissible modification is the reduction of the ports by moving a and c to the left. The faces, $a\,a'$, $b\,b'$, of the valve, it is plain are as narrow as they can be made with the port of its present breadth, each being equal to half the travel. Nor can they be made any less, however much the ports are reduced—for since that must be done by moving a and c to the left, a' cannot be moved any farther than those edges are, because it would then pass beyond c to the left, opening the port again when the valve is at the other end of its travel—just as a mere inspection of the figure shows that we cannot cut anything off the edge b.

17. If the ports be reduced, a representation of this arrangement with all the parts occupying the relative positions in which they have thus far been uniformly shown, would be less explanatory, and the modified action less readily traced than if some changes be made. For this reason, and also for the sake of more easily comparing the operations of the three varieties of valves, the next six figures have been drawn and arranged as they are. The breadth of the port is the same in all, being one-fourth of the travel, or half the radius of the circle described by the eccentric. In each case the valve

is shown in two positions: first, when it is just opening the port, and, second, as it will be at the end of half a revolution; the eccentric being shown in its proper place in each case, and the direction in which it turns indicated by the arrow.

18. Figs. 12 and 13 represent the arrangement first discussed, in which the port is opened and closed while the eccentric moves from *e* to *g*, and remains closed during the completion of the revolution; the breadth of the valve, as before shown, being equal to the travel.

Figs. 14 and 15 represent the modification in which the valve is less than the travel, by the breadth of the port. In this case also, the port is opened and closed by the movement of the eccentric from *e* to *g*: but it remains closed only until *half* a revolution from *e* has been made, after which it is again opened and closed by the passage of the eccentric through an arc *h i*, equal to *e g*, remaining closed thereafter until the second half of the revolution is completed.

19. Figs. 16 and 17 represent the third arrangement, in which there is an opening in the valve, as large as the port, having on each side a face equal to half the travel. The effect produced is identical with that of the preceding combination—that is, the port is opened and closed in each *half* of the revolution, by the movement of the eccentric through equal arcs in each. But it is produced in a different way, requiring a perforated instead of a solid valve. And a most striking and distinctive feature of this movement is, that the chords of the arcs just mentioned, which may be called the chords of action, are in this case *parallel* to L M, instead of perpendicular to it as in the others.

20. These, then, are the three modifications of which the slide valve, operated by an eccentric, is capable. It has seemed best to describe them by themselves, before considering them as connected with the engine, because the whole nature of the movement, the things which it can do and the way in which it does them, could be more clearly explained by isolating it.

And again, the reader, thus familiarized with all the peculiarities of the combination in the abstract, will be able to trace with greater ease the application of such of them as may from time to time be brought into play. It is therefore proper to conclude this preliminary discussion with the following synopsis, which gives the salient features of its results, and shows at a glance the family likeness as well as the individual peculiarities of the three modifications of the movement.

21. The "Use of Valve" indicates its office as applied to the steam engine. The movements are numbered 1, 2, and 3, respectively, in the order in which they have been previously considered; the travel is supposed to be given, and the widest port, as well as the narrowest valve, which can be employed in either movement, are given in terms of this travel. The *chord of action* referred to is that of the arc through which the eccentric moves in opening and closing the port; then letting

$$t = \text{Travel of Valve};$$
$$p = \text{Greatest Breadth of Port};$$
$$b = \text{Least Breadth of Valve};$$

the synopsis may be conveniently arranged as follows, it being borne in mind that the port, at this extreme limit of breadth, is closed only at one or two *instants* in the revolution of the eccentric:

SYNOPSIS.

Use of valve.	Breadth of port.	Breadth of valve.	Port opened and closed in each revolution.	Relation of chord of action to line of motion.
Main slide .... 1.	$p = t$	$b = t$	Valve solid...... once	Perpendicular.
Independent cut-off 2.	$p = \frac{1}{2}t$	$b = t - p$	Valve solid...... twice	Perpendicular.
Independent cut-off 3.	$p = \frac{1}{2}t$	$b = t + p$...	Valve perforated..twice......	Parallel.

CHAPTER II.

INVESTIGATION OF THE ACTION OF THE VALVE, AS APPLIED TO A SINGLE STEAM PORT.

22. In examining the special application of the slide valve to the steam engine, we have first to consider what the requirements of the engine are; for the valves, of whatever kind, being to that machine what the lungs are to the body, must necessarily be so actuated as to regulate the admission and escape of the steam, which is its breath, in accordance with the conditions imposed by the motion of the piston. Now the admission of steam is one thing, and its escape is another; and though both may be regulated by what is called one valve because it is made in one piece, yet this is not by any means necessary. Four separate valves may be and sometimes are employed—a steam and an exhaust valve at each end of the cylinder; and even when the functions of all these are, as in the three-ported or common slide valve, performed by one piece, these functions are none the less distinct; that arrangement is, then, a complex, though not a complicated, system of valves. Therefore, taking up these functions separately, we will first consider a valve as having for its sole duty the admission of steam into one end of the cylinder. We will also suppose that there is no "lead;" in other words, that the port is to be opened at the precise instant when the stroke of the piston begins.

23. It is evident that the admission cannot continue any longer than the stroke does, so that by the time that is completed, the valve must have opened and closed the port. And it is equally evident, that the port, once closed, must remain closed during the whole of the return stroke of the piston. These conditions determine at once the modification of the movement which must be used, and the greatest breadth of the port for any

assumed travel. The fact that the port must be opened and closed but once in each revolution, limits us to the use of the first of the three modifications previously described; and the breadth of the port is determined by the consideration that, as explained in connection with Fig. 8, the eccentric, through whatever arc on one side of L M it may act to open the port, acts to close it through an equal arc adjacent to the first, on the opposite side of that line.

24. For, since both operations must now be performed in just half a revolution, each of these arcs must be equal to 90°, and consequently the breadth of the port will be half the travel, as shown in Fig. 18. The angular position of the eccentric is also thus fixed; for this must be such that the port shall be opened at the instant the stroke begins—and a glance at the figure shows that in order to have this take place, the eccentric must be placed at either g or h. It makes no difference, of course, so far as the action of the valve is concerned, which of these points is selected; but if it be h, as shown in the figure, the revolution must be in the direction indicated by the arrow; if it be g, this direction must evidently be reversed.

25. In Figs. 3 and 5 were given representations of engines, arranged in the simplest possible way, with direct connections between the piston rod and the crank, and between the valve-stem and the eccentric, the latter being fixed on the main shaft. By comparing Fig. 3 with Fig. 18, we see that the relative positions of the parts are alike in both, the piston being at the beginning of its stroke, or, as it is commonly expressed, "the engine being on the dead centre." And the position of the eccentric, which is determined by the considerations just explained, illustrates another very common expression, that "the eccentric is set at right angles to the crank." This is only true necessarily, when the connections *are* direct, as shown, or such as to be equivalent to them. In the abstract, it must be understood, that the "angular position of the eccentric," means *its angular position in relation to the line in which its motion is transmitted, at the beginning of the stroke of the piston.* It is not by any means obligatory that this line shall be parallel to

the face of the valve: we have made it so in our diagrams for the sake of simplicity—but in practice we may do otherwise for the sake of convenience; by the introduction of rock-shafts, levers, and links, we may give the eccentric rod any direction we please. But, keeping in mind that all these links are supposed to be of infinite length, or that the "vibrations" and consequent irregularities are compensated for by devices similar to that shown in Fig. 5, it is clear that all these changes in the *direction* of the motion do not modify its nature. Consequently the line in which the eccentric's motion is first transmitted, whatever its absolute direction, corresponds to the line L M; and upon it may be drawn, if we choose, a valve situated with regard to the eccentric shaft, precisely like the one shown in Fig. 18.

26. Again, the connection between the piston rod and the main crank need not be direct; it also may be modified by the introduction of a rock-shaft and lever, of which a notable instance is seen in the Vibrating Lever Engines of Capt. Ericsson, so well known from their use in the Monitor Iron-Clads.

Nor need the motion of the valve be parallel with that of the piston, even if the connections are all direct; the valve face has sometimes an inclination to the axis of the cylinder. And, finally, there need not be any main crank at all; we may if we choose make use of a sun and planet wheel, or other device, in order to procure the rotatory motion.

27. From these considerations we see, that if such expressions as "the eccentric is at right angles to the crank," and "the eccentric is ahead of the crank," are true in regard to such an engine as that shown in Figs. 3 and 5, they are so only by accident; the position of the eccentric is determined in relation to the line in which its motion is transmitted, by reference to the position of the piston; and the crank, if there be one, must take care of itself, and may have any conceivable position in reference to the eccentric. Still further, it is to be noted that the line joining the centre of the eccentric with that of the shaft on which it is fixed, will be at right angles to L M at the beginning of the stroke, only in the special case here illustrated, in which the eccentric must make half a revolution in order to open and close the port.

The chord of the arc, be the same greater or less, through which it must move in order to do this, is in all cases perpendicular to L M; and therefore will only pass through *o*, when that arc, as here, is equal to 180°, thus admitting steam from the exact beginning to the very end of the stroke. So that the first of the expressions alluded to, at least, *can* be strictly true only of an engine which "follows full stroke without lead."

28. We have ascertained the particulars of the construction and arrangement of a valve adapted to the engine under these conditions; let us now see what will result from the only modification possible, a reduction in the breadth of the port. In Fig. 19 we have a valve precisely like that shown in Fig. 18; but the edge *c* of the port is moved to the left. The piston being at the beginning of the stroke, the port ought instantly to be opened. Erecting as before a perpendicular at *c*, it is obvious at a glance that in order to open the port, the eccentric must be advanced from its former position to the point *g*, and when that is done, that it will act to open the port while passing through the arc *g f*, and to close it while describing the equal arc *f h*. The whole arc *g f h* being now less than a semicircumference, it follows that the piston cannot have completed its stroke by the time the port is closed. In other words, instead of "following full stroke" as before, the engine now "cuts off" at a point determined by the length of the arc *g h*.

29. A comparison of these two figures, 18 and 19, will give a clear insight into the mystery of "lap." In each case the valve is at half stroke; in the latter the valve overlaps the port on the opening edge, while in the former it does not; in one case the valve is said to have lap, and in the other not to have it.

It is a very common expression, that in order to make the engine cut off, we "add lap to the valve;" but it is very clear that, in this case at least, we do no such thing. Other things remaining unchanged, we partially stop up the port; the valve *has* "lap," to be sure—but it comes into possession of that treasure accidentally, as a result; it is not a cause, but an effect. The

real *cause*, it is necessary to observe, is not the reduction of the port, but the change in the angular position of the eccentric ; *that* is what effects the cutting off of the steam, and gives the valve "lap" when at half stroke. These things it does of necessity ; and it permits us to make the port actually smaller, if we choose.

30. It is not necessary that we should do so, however ; if, as in Fig. 20, we advance the eccentric to the position given in Fig. 19, without changing the port, it will be seen that in order to have the latter opened just at the beginning of the stroke, we must now add a piece to the valve, equal to $i\,o$, the distance through which the eccentric has moved it in reaching its new position. The operation of this arrangement will then be exactly similar to that of the preceding one. The port will be opened and closed while the eccentric moves from g to h, so that the steam will be cut off at the same point ; and when the valve is at half stroke, it will have the same lap, $i\,o$, as before. If we have in this case actually added to the valve, this addition is made, and becomes "lap," in consequence of the change in the angular position of the eccentric ; so that it is now, no less than before, an effect, not a cause.

31. It needs no reflection to see that if we had made the valve wider *without* changing the position of the eccentric, we could have made no use of the addition, and in order to have the port opened at the right moment, would have been obliged to push the valve bodily to the left, just as much as we had increased its breadth, thus depriving it of its lap, and letting the steam follow full stroke as at first. It is also to be noted that although in Fig. 20 we have not reduced the port in fact, we have in effect, because it will not now be fully opened ; the position of the eccentric being the same as in Fig. 19, the valve can move no farther to the left in one case than in the other. It is of no use to have the port so wide that it cannot be fully opened ; we have all along supposed it not to be ; and since if we do not stop up the surplus opening, the valve does, it was perfectly correct to speak as we did of a reduction in the breadth of the port as the

only possible modification in the arrangement adapted to a full stroke engine.

32. We have spoken thus fully in regard to this matter of the lap, or cover, of the valve, because it is our aim to point out as clearly as may be the actual reasons of things ; and this expression, "adding lap to the valve," is often used in a manner calculated to mislead ; the lap is spoken of as the cause of the change in the action of the valve, leaving the fundamental modification, namely, the altered angular position of the eccentric, quite in the dark. The whole matter, which is sometimes thus made to seem very mysterious, will, we think, be perfectly clear on an examination of Figs. 19 and 20, and may be thus simply stated : if the angular position of the eccentric be such that the valve when at half stroke overlaps the port on the opening edge, the opening of the port will be less than half the travel by an amount equal to the lap, and, the port being opened at the beginning of the stroke of the piston, will be closed before the end.

33. We have now, considering the valve as performing the single duty of admitting steam into one end of the cylinder, ascertained the conditions of its action, and the limits thus imposed on its construction ; the whole being summarily comprehended in the following propositions :

1. The greatest possible opening of the port is half the travel of the valve ; in this case the steam is admitted during the whole stroke of the piston, at the beginning of which the valve, which has no lap, is at the centre of its travel.

2. If the eccentric be so placed that at the beginning of the stroke of the piston the valve is not at the centre of its travel, the opening of the port will be reduced, and it will be closed before the piston completes its stroke.

3. In this case, the opening of the port will be less than half the travel, by as much as the valve, at the beginning of the stroke of the piston, varies from its original central position. And when the valve is at half stroke it will overlap the port on the opening edge to the same extent.

4. The point in the stroke of the piston at which the port will be closed and the steam cut off, will depend upon the angular position of the eccentric at the beginning of the stroke.

34. The valve as adapted to engines following full stroke, requires no farther consideration ; it remains then for us to consider its adaptation to those in which it is required to cut off the steam at any given point in the stroke.

Supposing then, as heretofore, that the port is to be fully opened, there are three prominent elements to be taken into account; viz., the travel of the valve, the breadth of the port, and the point of cutting off: which may be varied at pleasure. The angular position of the eccentric, which we have found to exert a controlling influence, is not overlooked ; inasmuch as it has fixed relations to the other elements, it will be determined by them if they be first decided on. The question with which we have to do may, therefore, present itself in practice in three forms—for we may be required to find either of the three elements, the other two being given—thus, we may have,

1. Given, the breadth of the port and the travel of the valve, to find the point of cutting off.

2. Given, the travel and the point of cutting off, to find the breadth of the port.

3. Given, the breadth of the port and the point of cutting off, to find the travel of the valve.

35. No mention is here made of the lap, because that, as well as the position of the eccentric, will be determined as a consequence of a determination of the other elements. We have arranged these in this order, because the solution of the problem in the form first given, will, as we think, be more readily explained by the aid of a diagram similar to those thus far used.

Thus, referring to Fig. 19, we suppose the breadth of the port, *c d*, and the travel of the valve, to be given.

Let the circle in the diagram, Fig. 21, corresponding to that in Fig. 19, represent the path of the eccentric, and the diameter $f\ l$, the travel of the valve. From f, lay off $f\ i$ toward l, equal to the given breadth of the port. Draw through i the chord $g\ h$, perpendicular to $f\ l$; this corresponds to the perpendicular erected at c, in Fig. 19, and as shown in connection with that figure, g will be the proper position of the eccentric at the beginning of the stroke of the piston, the revolution being in the direction of the arrow, and $g\ h$ will be the arc through which the eccentric must pass in order to open and close the port; or, in other words, to cut off the steam.

36. Now we have seen at the outset, that the motion of the valve is in all respects similar to that of the piston, and has the same relation to it, as though a crank were used for converting the latter into rotatory motion, whether that be actually the case or not. Consequently, the circle may also represent the path of the main crank, if there be one; and a diameter of it will properly represent the stroke of the piston, whether there be or not. And since this stroke must begin when the eccentric is at g. it follows that the diameter $g\ k$ is the one which must be thus used.

The resemblance to the preceding figures is so close that nothing need be said in explanation of the action of the valve. It is evident that if a slotted cross-head, as indicated in faint lines, be placed at right angles to $g\ k$, it will be moved by the crank-pin, exactly as the piston must move; and letting fall from h, the point reached by the eccentric when the port is closed, $h\ p$, perpendicular to $g\ k$, the distance $g\ p$ will clearly be that travelled by the piston up to that time; or, in other words, p will be the point of cutting off, $g\ k$ being the length of the stroke, and g the beginning.

37. This simple diagram, then, gives a ready solution of the problem in its first form. It was before ascertained that the breadth of the valve must be equal to the travel, and that the breadth of the port and the lap together are equal to half the travel. Therefore, making $f\ i =$ breadth of port, we have the lap $= i\ o$; the chord, perpendicular to $f\ l$, the line of travel, at i the opening edge of the port, gives at once g, the position of the eccentric at

the beginning of the stroke of the piston, and $g\,h$ the arc which it must describe before the steam is cut off; and the perpendicular $h\,p$, to the diameter $g\,k$, gives $g\,p$, the distance followed. And the second form is obviously solved by a mere inversion of this process: first, considering any diameter, $g\,k$, as the stroke of the piston, set off $g\,p$, the distance to be followed; then erecting $p\,h$ perpendicular to $g\,k$, we have $g\,h$, the arc to be described by the eccentric during the opening and closing of the port. And since the chord of this arc is perpendicular to the line of motion, we have but to draw a diameter $f\,l$, at right angles to $g\,h$, in order to determine that line, when g, as before, will be the position of the eccentric at the beginning of the stroke of the piston; and $f\,l$ representing the travel of the valve, $f\,i$ will be the breadth of the port, and $i\,o$ the lap of the valve when at the centre of its travel.

38. The solution of the third case, in which it is required to determine the travel of the valve, the breadth of the port and the point of cutting off being given, requires but one step in addition. Thus, in Fig. 22, taking any diameter, $g\,k$, as the stroke of the piston, setting off $g\,p$, the distance to be followed, and proceeding as before, we find $f\,i$, which would be the proper breadth of the port, if the circle were of the right diameter. If the given breadth be greater or less than $f\,i$, the diameter of the circle must be increased or diminished in the same proportion.

Suppose it to be greater: prolong $i\,f$ to n, making $i\,n$ equal to the given breadth; draw $n\,m$ parallel to $f\,g$, cutting $i\,g$ prolonged in some point m, through which draw $m\,r$ parallel to $g\,o$, cutting $f\,l$ in r; then $m\,r$ will be the radius sought, or half the required travel; for, from the similarity of the triangles thus formed, we have $r\,m : i\,n :: o\,g : i\,f$.

If the given breadth of the port be less than $i\,f$, the process is not changed in any particular; the points n', m', r', as shown, merely fall within the original similar triangle $f\,g\,o$, and the required radius $r'\,m'$ is less than $o\,g$, as it evidently should be.

39. "But," the young draughtsman will say, "here is a cylinder, with

the ports already made; and I am called on to tell how much *lap* the valve must have in order to cut off at a given point—or, what will be the effect of a given amount of lap?" Very likely; but a little reflection will show that these are the same questions which we have just been considering, in a slightly modified and less direct form.

Referring to Fig. 21, we see that if the travel be assumed, and it is required to follow through a fraction $g p$ of the stroke $g k$, we must, in the first place, have the eccentric set at g at the beginning of the stroke of the piston, $f l$ being the line of motion and the travel of the valve; that being done, the lap $i o$ follows as a matter of course; and conversely, if we have given a lap equal to $i o$, the eccentric must also be placed at g, and $g p$ will be the distance followed. The opening edge of the valve will move back to f, and as i is the opening edge of the port, it will be opened to the extent $i f$, if it be wide enough; it cannot be opened farther, no matter how wide it is; and if not so wide as that, the only remedy would be to cut away the edge f until it is.

40. It must always be borne in mind that the lap is dependent on the angular position of the eccentric; *that* is the element of prime importance, the point on which the others hinge. The necessity of first determining it will, perhaps, be more clearly seen from the consideration that it is the same for a given point of cutting off, whatever be the travel of the valve; as evidently we may consider any of these diagrams to be made upon any scale we please, without affecting the proportions which subsist between the parts. If then the third case had been put in the very common form, what must be the travel with a given *lap* in order to cut off at any given point, it is clear that Fig. 22 enables us to answer it just as readily as before; the only modification in the original construction being this, that after finding the point i, we set off $i r$ or $i r'$, towards o, making it equal to the given lap, and draw $r m$ parallel to $g p$ in order to determine the travel; after which the effective or possible breadth of the port is easily ascertained as before.

41. Having thus arrived at a simple and ready mode of constructing the

valve and its "movement" under the conditions and consequent limitations which adapt it to the office of regulating the admission of steam into the cylinder, it is proper, before proceeding farther, to explain one or two other modes, which, though in some respects less direct and obvious, may in others be thought preferable.

In Fig. 23 we have a diagram which exhibits the relations of the different elements in a very satisfactory manner. On any diameter, $f\,l$, representing the travel of the valve, describe a semicircle; draw a semidiameter o D at right angles to $f\,l$, and letting that represent the stroke of the piston, describe on it a circle representing the path of the main crank. Let it be required for example that the engine shall "follow" one-fourth of the stroke; let the stroke begin at o, and lay off $o\,a = \frac{1}{4}\,o$ D; draw $a\,a'$ parallel to $f\,l$, and also $o\,a'$, which prolong to A: from A let fall on $f\,l$ the perpendicular A A′. Then the main crank being supposed to turn *with* the clock and the eccentric *against* it, as indicated by the arrows, A o will be the proper angular position of the eccentric, f A′ the breadth of the port, and A′ o the lap.

42. The truth of this is not so evident at a glance as that of the foregoing constructions: since the main crank and the eccentric must in fact move in the same direction in the usual arrangements of engines, and in all cases with the same angular velocity. it is necessary to prove that the angle $o\,b\,a'$ measured by the arc $o\,a'$, is equal to twice the angle $f\,o$ A, measured by f A; for we have before seen that the arc described by the eccentric in opening and closing the port is bisected at f. If we draw the radius $a'\,b$, and join a' D, it will be seen that such is the case; for the angle $a'\,b\,o$ at the centre, is twice the angle a' D o at the circumference. Also a' D $o = f\,o$ A, each being measured by half the arc $o\,a'$—the first because it is inscribed in the circumference, the second because it is included between a tangent and a chord: $\therefore f\,o\,\mathrm{A} = \frac{1}{2}\,o\,b\,a'$.

This process may also be inverted with equal propriety, setting off f A′ = any given port, or o A′ = any given lap (the travel being in all cases assumed), then erecting the perpendicular A′ A, joining A o, and drawing $a'\,a$ parallel to $f\,l$, we find $o\,a$, the distance followed.

43. Another construction is given in Fig 24, in which $f\,l$ represents the travel of the valve, and the diameter $x\,y$, at right angles to it, the stroke of the piston. Setting off from x, the beginning of the stroke of the piston, $x\,a$ equal to the distance to be followed, and drawing $a\,a'$ parallel to $f\,l$, join $a'\,x$, and draw o A parallel to $a'\,x$. A will be the initial position of the eccentric, the directions of the revolutions being the same as before ; and letting fall from A on $f\,l$ the perpendicular A A$'$, we have f A$' =$ the opening of the port, and A$'\,o =$ the lap, as in the preceding diagram. In this also the angle $f\,o$ A $= \frac{1}{2}\,a'\,o\,x$:—for drawing $a'\,o$, we have in the isosceles triangle $a'\,o\,x$, the two angles $a'\,x\,o$ and $x\,a'\,o$, at the base, equal to each other, and each to A $o\,y$. Therefore the remaining angle $a'\,o\,x = 180° - 2$ A $o\,y$: half of this is $90° -$ A $o\,y$, which is equal to $f\,o$ A. The dotted semicircle described on the semidiameter $o\,y$, and the perpendicular to $o\,y$ drawn from the intersection of that semicircle by the line o A, sufficiently indicate the essential similarity of this to the preceding diagram : the only difference being that the whole diameter $x\,y$, at right angles to the line of motion of the valve, is here used to represent the stroke of the piston, instead of the half of it as in Fig. 23.

44. There is also a modification of Fig. 23, which gives the position of the eccentric, and the breadth of the port, in a manner equally simple, though less obvious. This modification is shown in Fig. 25. In this, $f\,l$ as before representing the travel of the valve and its line of motion, let the radius $f\,c$ represent the stroke of the piston, which is supposed to begin at f, the paths of the main crank and of the eccentric being as before represented by the smaller and the larger circles. From f lay off $f\,p$, the distance to be followed ; erect the perpendicular $p\,a$, draw $c\,a$, and prolong it to A : then A will be the proper position of the eccentric, the segment A a the opening of the port, and $a\,c$ the lap.

The truth of the proposition as to the angular position of the eccentric is evident, from the fact that the angle $f\,c\,a$, at the circumference, is half the angle $f\,o\,a$, at the centre of the smaller circle.

The opening of the port, according to the previous construction, would have been found by letting fall from A on $f\,l$ the perpendicular $A\,m$. But the triangle A $c\,f$ being isosceles, the side A c will be divided by a perpendicular from f upon it, into parts respectively equal to those into which $f\,c$ is cut by A m: therefore since $f\,a\,c$, being inscribed in a semicircumference, is a right angle, we have A $a = f\,m$, = breadth of part, and $a\,c = m\,c =$ lap.

It is so obvious, that we need but point out the fact, that if the breadth of the port be given, (the travel being assumed in all these cases), the point of cutting off may be found as readily as in the preceding constructions, by setting off $f\,m$ equal to the given breadth, erecting the perpendicular m A, drawing A c, and dropping the perpendicular $a\,p$ from the intersection a of the radius A c with the smaller semicircle, upon the line $f\,l$.

45. In regard to Case 3d, that is, given the breadth of the port (or the lap), and the point of cutting off, to find the travel, it is evident, keeping in mind as explained in connection with Fig. 22, that the angular position of the eccentric is the same for any travel, that we have only to construct a diagram by either of the methods just explained, or any equivalent one, assuming any travel at pleasure, of a movement adapted to cutting off at the given point.

Then, the linear elements being functions of the angle ($f\,o$ A, Fig. 23), subtended by the initial position of the eccentric with the line of motion, and having fixed proportions to each other, the travel may be increased or diminished to suit the given lap or port, as explained in connection with Fig. 22.

We have thus endeavored to point out to the beginner what seems to us the shortest and most direct path to a clear comprehension of the nature of the valve movement derived from an eccentric, in its elementary form, and of the limitations of its capabilities, inherent in itself, and arising from the conditions under which alone it can be adapted to practical use in the steam engine; and leave him to strike out other paths, should he desire to know them, by his own ingenuity and application.

CHAPTER III.

INVESTIGATION OF THE ACTION OF THE EXHAUST VALVE, OF THE THREE-PORTED OR COMMON SLIDE, AND OF THE TWO-PORTED OR BOX VALVE.

46. It will, no doubt, be remarked that all that has thus far been said does not explain the operation of the most common form of the valve, which by the sliding motion controls both the entrance and the exit of the steam, and that at both ends of the cylinder.

This is true, and with purpose. For it is necessary that the steam should get into one end of the cylinder before it gets out, and before it gets into the other. And a valve which could not regulate one of these operations, would hardly be competent to control them all; besides, it seemed to us that the discussion would be made more simple and the results more obvious, by confining it at first to the consideration of one port for one purpose. And we preferred to examine first the action of the valve as arranged and used for the admission rather than the escape of the steam, because thus, while the whole movement was equally well illustrated, the effects of modifying the proportions of its elements could be more appropriately shown.

47. Let us now see what is required of the valve in order to render it capable of controlling the reverse process. Just because it *is* the reverse process, it is natural to infer that the action of the valve has simply to be reversed—so that the port shall be open, while before it was closed, and *vice versa.*

And this is strictly true, if the engine follows full stroke; in which case it is clear that a port may be open at each end of the cylinder, for the entrance of the steam on one side of the piston and its escape on the other, during the entire stroke; or, during a half revolution of the eccentric.

Referring to Fig. 18, we see that the valve there shown, and discussed

as a steam valve, will operate equally well as an exhaust valve, if we do either of two things : namely, reverse the direction of the revolution, or the position of the eccentric. The piston *must* move to the left ; so that, steam being admitted on the right by another port, the one shown, now controlling its escape, must remain closed until the end of the stroke ; and it will do so, evidently, if the direction of the revolution, indicated by the arrow, be reversed, or if the eccentric be placed at g instead of h, without changing the direction of the revolution.

48. Retaining our original supposition, that the valves are set with no lead, the same limitation applies to the time during which the exhaust port can remain open, that we found to be true in regard to the steam port ; for it certainly must be closed as soon as steam is admitted, and must remain closed during the whole stroke, in order to be just opening when the piston begins to return.

Since, then, the port must be opened but once in the course of the revolution, and can not be open during more than half of it, we can not go beyond the limit shown in Fig. 18 :—using a valve of the first kind, and making the breadth of the port equal to half the travel.

But we may stop short of that limit, as we did with the steam valve ; we may make the port narrower, so that it will be closed before the stroke is completed ; thus in fact "cutting off" the escape of the steam : which is technically called "cushioning on the exhaust," and, within narrow limits, is found of advantage in engines running at a high speed, in arresting without shock the momentum of the piston and its attachments.

The whole arrangement, then, being precisely like that of the steam valve, the diagrams and modes of procedure explained in the preceding chapter apply equally well to the construction of the exhaust valve and its "movement," which therefore require no farther independent discussion.

49. Hitherto, for reasons already given, we have supposed each valve, of whichever kind, to govern only one port ; thus requiring four in order to make the engine work. But even if four ports are used, it is not necessary

that the valves should be independent of each other and worked by separate eccentrics. If, for example, the steam valve at one end of the cylinder be rigidly connected to that at the other, it will be seen that one eccentric will operate them both.

Thus, in Fig. 26, we have a "full stroke" engine, with the steam valves at the opposite ends of the cylinder so connected as to form but one piece; the piston being at the beginning of a stroke, the valves must be at half stroke—there being of course no lap, as shown.

It must be observed, that the opening edges of the two ports have opposite relations to the valves, when considered in reference to the motion. In the given position of the eccentric, the valve moves to the left; and it is to be kept in view, that while the opening edge of the port *a* is at the right, that of the port *b* is on the left, so that the former is just opening, while the latter is just closing; and the one will stay open, the other closed, during the whole stroke, or half a revolution, when the valves will have returned to their present position. The eccentric having then reached the point *g*, it is plain that the port *b* will be opened, and the port *a* closed, during the return stroke of the piston. It is therefore evident that whether *a* and *b* be used as steam ports or as exhaust ports, the two valves will be actuated by one eccentric in exact accordance with the requirements of the engine following full stroke without lead.

50. But the two valves thus connected may be arranged, as in Fig. 27, so that the opening edges of the two ports shall be on the same side. In this case, the breadth being equal to half the travel as before, each port will be open during half a revolution; but since they are both open at the same time and closed at the same time, it follows that if one be used as a steam port, the other must be used as an exhaust port, when, as in Fig. 26, one eccentric will operate the two valves so that the engine shall follow full stroke without lead.

Again, if we suppose the ports to be narrowed equally from their opening edges, as in Fig. 28, the ports at the opposite ends of the cylinder will

be closed at the same point in the stroke; for an examination of the figure shows that the valves not only overlap the ports equally when the eccentric is in the position represented, but after half a revolution will do so again; so that to open and close a port in either case, the valves must move through the same distance and the eccentric through the same arc. In this arrangement, then, if *a* and *b* are two steam ports, they are controlled by one eccentric so that the engine follows equally in both the direct and the return stroke of the piston; if they be two exhaust ports, the engine cushions equally at each end of the cylinder, the whole movement in either case being perfectly adapted to the purpose for which it is designed.

51. Since, in the arrangement shown in Fig. 27, the relations of each valve to the opening edge and to the motion are identical, it is obvious that *the two ports will be opened and closed simultaneously*, whether they be of the breadth there shown, or narrowed equally from their opening edges. In the latter case, it will be seen hereafter that this circumstance which we have emphasized imposes limits upon the extent to which the reduction of the ports can be carried; for it must be kept in mind that one of them being a steam port, the other must be used for the opposite purposes of the exhaust.

The distance between the two ports, *a* and *b*, in these last illustrations, is entirely arbitrary; we may increase or diminish it at pleasure, or according to circumstances. We may, for illustration's sake, imagine it to be reduced to zero—supposing an impervious plane to separate them. In that case, it follows that one *valve-face*, of a breadth equal to the travel, would govern both ports. But we do not wish the reader to lose sight of the circumstance that there are in fact two *valves:* there are certainly two ports, and neither of them would be of use without a valve; and *with* a valve, either of them can be used without reference to the other. If it is a steam-valve, to follow full stroke, there will be no lap; if it be a cut-off valve, there will be lap, whether another, or a dozen more, be attached to it or not.

52. There are two reasons for thus emphatically calling attention to this point. One is, that in speaking of the lap of the valve, we use that term to indicate the lap of *one* valve over the edge of *one* port. This, because there need not be more than one port, and its valve *will* have lap if it is to close before the end of the stroke. We know that there are those who, in reference to a three-ported slide-valve, speak of the "lap" as meaning what they call the *whole lap;* that is, the lap at both ends taken together. We must confess our inability to see any reason for this; it certainly cannot be denied that a single cut-off valve has "lap" over the edge of its port when at the centre of its travel, and as it is not necessary to connect another one with it, why should the lap of this possible addition be added to that of the first?

The other reason is, that the keeping constantly in view this distinction between the two valves, however close the connection between them, will be found of great advantage in examining the operation of this same three-ported valve, which comes next in order; for this, as before intimated, combines in itself, in one piece, the whole system of four valves, which are requisite to the working of the engine.

But if we choose, in accordance with common usage, to speak of one sliding piece as *a valve*, without reference to the number of the ports which it governs, we have, thus far, reached these conclusions: that the requirements of the engine may be met by the use of two valves, one for the admission of steam, the other for its escape; and that these valves may be so constructed as to cut off the steam at any given point in the stroke, while the exhaust may or may not continue during the whole stroke.

53. But the motion of a valve governing two steam ports, at opposite ends of the cylinder, is necessarily such that the steam can enter only one of them at a time; and since it might go out through the same port at which it came in, the valve may be so contrived as to allow it to escape through one while entering the other; thus practically simplifying the whole arrangement by reducing the number of parts, making use of only one sliding valve, and two ports into the cylinder.

In Fig. 29 is represented the arrangement which is usually adopted for accomplishing this result, known as the "three-ported slide-valve," from the three ports of the valve seat.

Of these, the two outside ones, C, C′, correspond to the ones shown at *a* and *b*, Figs. 26, 27, and 28—one communicating with each end of the cylinder. Between them is a third port, E, which leads to the open air or to the condenser, as the case may be. By the motion of the valve from side to side, this port E is brought alternately into communication with the two ports C, C′, through the intervention of a cavity, G, in the face of the valve.

54. The breadth of this third port, and the distances between its edges and those of the steam ports C, C′, may be varied at discretion; but obviously they should be such that when either of the latter is fully open on the outer or steam side, the other should have at least as free an opening for the escape of the steam from the other end of the cylinder.

In the figure, the valve is shown as arranged to follow full stroke, all the parts being in their proper relative positions; and a glance at it shows that as the steam will enter through one port and escape through the other during the whole stroke, its operation is precisely equivalent to that of two valves like that shown in Fig. 26, one for steam and the other for exhaust.

55. In both cases, the opening edges on the steam side are the outer edges; so that, whether the ports retain their full breadth or are reduced as in Fig. 28, the valve, considered as a steam valve only, is equivalent to a solid block, in which we are at liberty to form the cavity G, to accommodate the exhaust, or for any other purpose; and we may make it of any size, so long as we leave the faces D, D′, as wide as the ports C, C′, in order to prevent the steam from passing directly around those faces without entering the cylinder.

56. But when the ports are opened for the escape of the steam, it is from the *inner* edges, so that in fact the *action* of this arrangement is precisely like that of the one shown in Fig. 27; as no matter in which direction

the valve moves from its position in Fig. 29, one port is opened to steam and the other to the exhaust. If then these ports be reduced, the operation of the combination will only be equivalent to that of two valves like the one shown in Fig. 26, when they are reduced equally *from both edges.* When this is done the steam will be cut off, at any desired point in the stroke; but since the ports close simultaneously, the escape of the steam from before the advancing piston ceases, at the same instant when its admission ceases behind it: so that what is left of the stroke must be made against a constantly increasing back pressure, by a constantly diminishing impelling power.

57. So long then, as the opening of the ports is equal to half the travel, and the engine follows full stroke, this combination fulfils perfectly all its requirements; but as soon as we attempt to make it perform the duty of cutting off the steam, the action on the exhaust side is deranged.

The cause and nature of this derangement, in one case, have just been alluded to. But the whole matter will perhaps be made more clear by first considering the case illustrated in Figs. 30 and 31. As before remarked, the escape of the steam is a thing entirely distinct from its entrance, although the same port answers for both purposes; and although the port C, for instance, is covered by one *valve-face*, the force of the distinction on which we have insisted, by which that valve-face is to be regarded as two *valves*, will be seen from the consideration that it opens the port on the right for steam, but on the left for exhaust. In the full-stroke engine, Fig. 29, the breadth of this valve-face being precisely equal to that of the port, the valve is at mid-travel when the stroke of the piston begins, and there is neither lap nor lead on either the steam or exhaust side of the ports.

In order to make the engine cut off, it is necessary to reduce the opening of the ports on the steam side, as shown in Fig. 30, in which the valve is also shown at mid-travel; the valve-faces overlapping the ports at the outer ends. No change has been made in the *exhaust* part of the valve; the

cutting-off being a function of the steam side only, the ports have been narrowed from the outer edges only, leaving the inner ones as they were.

58. The effect produced on the action of the *exhaust valve* by this, is shown in Fig. 31, in which the eccentric has been advanced to its proper position at the beginning of the stroke, so that the port C is just opening to steam.

The other port C′, therefore, must be opened to an extent just equal to the lap on the steam side shown in Fig, 30, that is, just as much as the port was reduced. But it is open from its inner edge ; in other words, the exhaust-valve has what is technically called "lead," since it opens *before* the stroke of the piston begins.

The consideration of this modification has hitherto been excluded for simplicity's sake ; it is now forced upon us, and its nature clearly illustrated by a comparison of these two figures

59. The exhaust valve in this case, it will be observed, has "lead" as a matter of *necessity*, just as the steam valve has "lap," and both these things depend on the angular position of the eccentric. Having determined that, the steam-valve must be set accordingly ; and the exhaust valve moves with it, only because it is in one piece with it. But if we return to the consideration of a valve governing one port for one purpose, it is clear that we may advance the eccentric at pleasure beyond the position hitherto assigned it, so as to have the port open at the beginning of the stroke, to any desired extent, whether it be a steam port or an exhaust port. This is "giving lead" ; its object being, in the case of the steam valve, to admit so much steam as will fill the ports, passages, and the clearance between the piston and the cylinder head, so that at the beginning of the stroke, there shall be acting upon the piston, steam of the full working pressure. And it is sometimes carried beyond that, for the purpose of aiding in arresting the momentum of the piston and its connections. On the other hand it is plausibly argued that this can be more economically done by "cushioning on

the exhaust," as before explained, since the power required is extracted from steam which, having done its work in the engine, is on its way out, and might as well be impressed into this service, as to be allowed to escape, and leave the work to be done by a fresh supply.

60. Opinions differ exceedingly in regard to this, however; which is not so much to be wondered at, because the circumstances vary so much in different cases. But, as we have said, we do not pretend to decide disputes of this kind, our object being to show how to construct the movement so as to accomplish the result which in the judgment of the reader is most desirable.

Lead may also be given to the exhaust valve; the object being to give the steam behind the piston ample time and opportunity to escape, so that upon the return stroke less back pressure shall be opposed to the useful effect of the steam which causes it, as well as to diminish the momentum of the piston when approaching the end of the stroke, by removing the impelling power.

61. In Fig. 32 is shown a valve whose port is equal to half the travel, being precisely like the one shown in Fig. 18; but instead of being arranged without lead as there, the eccentric is now advanced from g to e, at the beginning of the stroke. Under these circumstances, an inspection of the diagram shows that, as before, the port will be closed when the eccentric reaches h; in other words, as that is before a half revolution from e has been made, it will be closed before the stroke is completed.

How much before is readily ascertained; for in order to complete the half revolution, after closing the port, the eccentric must move through the arc $h\,e'$; from e' draw $e'\,d'$ perpendicular to $g\,h$: then, if $g\,h$ represents the stroke of the piston, $d'\,h$ will be that portion of it which will be performed while the eccentric describes the arc $h\,e'$. And since the arc $g\,e$ is equal to $h\,e'$, it follows that the port is opened when the piston has yet to move through a distance $d\,g$ equal to $d'\,h$, before beginning

the stroke. It appears, then, that an engine which without lead follows full stroke, will cut off a little before the end of the stroke, if lead be given to it.

62. This, practically, instead of being undesirable, is quite the reverse; and besides, this effect is so slight, that it is usual to arrange the ports as we have described, and adjust the lead by moving the eccentric ahead until the result is satisfactory. But if we will be precise about it, and insist that the engine shall have lead and still follow to the very end of the stroke, we must overstep the limit previously ascertained, and make the port wider than half the travel, as shown in Fig. 33. Here, the eccentric being at e at the beginning of the stroke, will evidently close the port at the end of it, after describing the half revolution $e\,h\,e'$; but the port is now wider than half the travel, the excess being equal to $d\,f$, one half the linear lead assumed.

63. We may, evidently, give lead to a valve which cuts off as well as to one that does not; and if we do, it will cut off a little sooner than before.

For example, in Fig. 34, we have a port, to open and close which the eccentric must move from f to f'. If there be no lead, we find the point of cutting off, as before shown, by drawing $f'\,A$ perpendicular to the diameter $f\,k$, which represents the stroke of the piston. If now we give lead, by placing the eccentric at e, as shown, when the stroke begins, the arc through which it must move in order to close the port is diminished by the portion $e\,f$; and this being equal to $e'\,f'$, $f\,e'$ is equal to $e\,f'$; therefore, drawing $e'\,A'$ perpendicular to the same diameter $f\,k$, as before, we find $f\,A'$, the distance followed with the given lead.

64. The perpendicular distance $c\,d$ between the chords $e\,e'$ and $f\,f'$ being equal to the lead, we may readily ascertain by a reversal of this process, the breadth of the port and the proper adjustment of the parts in order to cut off at any desired point with a given lead. Thus in Fig. 35, let the circle represent the path of the eccentric, and also that of the main

crank. Draw any diameter $f\,k$, and letting it represent the stroke of the piston, lay off f A, the distance to be followed; erect A e' perpendicular to $f\,k$; about f as a centre, with a radius $f\,l$ equal to the linear lead, describe an arc, and draw $e'\,m$ tangent to it. Draw also through O, L M perpendicular to $e'\,m$; it will be the line of motion, and $f\,f'$ perpendicular to it will determine $a\,b$ the breadth of the port, and e, where $e'\,m$ cuts the circumference, will be the position of the eccentric at the beginning of the stroke.

65. Fig. 33 also illustrates the state of things implied by the expression "*minus lap*," which means that the valve when at mid-travel is overlapped by the port. Although it was alluded to as if intended for the purpose of securing the admission of steam during the entire stroke even when lead was given, this arrangement is in practice applied only to the exhaust side, and that very rarely.

The figure shows the extreme limit to which it can be carried, the "minus lap" being one-half the lead, and the port consequently remaining open to the absolute end of the stroke; we may make it less, in which case the port will be closed sooner, but evidently we cannot make it greater. And in reference to Fig. 29, it was remarked that the faces D, D′ must necessarily be equal to the ports, C, C′, in breadth: it follows then that if such a valve be made with "minus lap" on either the steam or the exhaust side, there must be an equal positive lap on the other side, in order to prevent a direct communication between the steam supply and the escape, as shown in Figs. 36 and 37; a glance at which also shows that there will be a linear lead equal to twice the minus lap, on the same side, when the other side is just opening.

66. The constructions already given for determining the action of an eccentric upon one valve governing one port, may now, since they include all the elements that enter into the movement of the three-ported slide, be applied to the solution of problems relating to the latter, keeping in view its compound nature as really consisting of four separate valves.

A few words may, however, be added in regard to the derangement of the exhaust action, alluded to as resulting from the attempt to use this combination as an expansion valve. Briefly recapitulating, we found the valve shown in Fig. 29, having neither lap nor lead on either side, to be precisely equivalent in effect and similar in action to four single valves like that shown in Fig. 18, or to two double ones like the one represented in Fig. 27.

If, as in Fig. 30, the steam side of the port be reduced, we find that though we give no lead on the steam side, there will be on the exhaust side, as shown in Fig. 31, a linear lead equal to the steam lap.

67. The result of this may be found by a simple application of the diagrams, Figs. 21 and 32 ; in the latter figure it is to be remarked that if $h\,l$ be drawn perpendicular to $e\,e'$, we may let $e\,e'$ represent the stroke of the piston, in which case $e\,l$ will be the distance followed. It is therefore plain that in the diagram drawn over the valve in Fig. 31, if $e\,e'$ represent the stroke of the piston, the steam will be cut off behind it at A, and the exhaust closed before it at *a*. Had the same lead been given, without reducing the port, these two things would have taken place simultaneously at *a*. If, now, we wish to cut off at the same point, A, and yet to have no lead on either side, we can effect this by adding to the exhaust side of the valve an amount of lap equal to that acquired on the steam side by the reduction of the port, as shown in Figs. 38 and 39.

68. Under these circumstances, since the ports open and close simultaneously, the action again becomes identical with that of Fig. 27, and the suppression of both the supply behind and the escape before the piston will take place at the given point A. If, then, we attempt to cut off very early in the stroke by means of this valve, we are confronted by one of two difficulties : if we make no change on the exhaust side, we find the steam escaping before it has had a chance to do all its work ; if we equalize the lap, the steam is opposed in its effort to do its work by an injurious back pressure,

resulting from the too early closing of the exhaust port, which thus confines the steam before the advancing piston. The escape of the steam is now controlled by a movement specially arranged to regulate its entrance and suppression; and since the functions are distinct, this is clearly a faulty device, if we attempt to carry expansion very far by means of it. On the steam side the action is correct; but since it introduces a great lap on that side, we have, in these two cases, either the exhaust beginning too soon, if on that side we have all lead and no lap, or ending too soon if we add an equal lap and give no lead.

69. In this case it is correctly called *adding* lap; because, while on the steam side the lap comes of itself as a result of changing the angular position of the eccentric, we are not obliged to have any on the exhaust side. We may add it or not, as we choose; and, what is more, we may add more or less, up to a certain limit, which will be readily seen from a glance at Figs. 31 and 39, with a moment's consideration of the nature of the motion. In Fig. 31, the valve has been pushed bodily to the left by the angular advance of the eccentric; the exhaust port C′ is therefore open to that extent, since no change has been made on that side of the valve, whereas the opening edge of the steam port C has been moved to the left as far as the valve has, so that it is still covered. In Fig. 39, the exhaust port is also covered by the addition of an equal amount of lap. Now, if the eccentric be advanced still farther, so as to give *lead* on the steam side, we shall have the same lead on the exhaust side in Fig. 39, and so much more than there is already in Fig. 31; unless, in the former case, we choose to destroy it by adding so much more lap to the exhaust side. As it is necessary that the exhaust port should open at least as soon as the stroke begins, it is obvious that, having now made the exhaust lap equal to the sum of the lap and lead on the steam side, we have reached the limit, beyond which we cannot increase it; but we have the option of making it as much less as we think best.

70. This may be seen from another point of view, thus: in Fig. 29, the

valve is at mid-travel when the stroke begins. If by an angular advance of the eccentric the valve be moved a certain distance, it will pass beyond the opening edges of both ports alike, and if no change be made there will be so much lead on both sides. If this distance be considerable, we had before seen that the engine requires the steam port to be reduced by moving its opening edge nearly as far as the valve was moved, the difference remaining as lead, and the amount of reduction appearing perforce as lap when the valve is at mid-travel. But on the exhaust side we may *add* lap or not, retaining the whole or any part of the lead; the sum of the lap and lead on either side being equal to the distance from the central position at which the valve is placed when the stroke begins.

71. We are therefore enabled within these limits to compromise between the two sources of derangement on the exhaust side. "Lead" implies that a port is opened before the beginning, "lap" involves its being closed before the end, of the stroke; and one or both these conditions are imposed on the exhaust side, as well as on the steam side of this valve, unless it be made to follow full stroke. The results are good in moderation, but not desirable in excess; and it is evident from what has been deduced, that there is a limit beyond which expansion cannot be carried by the use of the three-ported slide-valve, without over-balancing the resulting gain by the unavoidable derangement of the exhaust action.

The determination of this limit is not within the scope of this treatise, which has to do with geometrical instead of physical considerations; so, leaving the reader to decide for himself at what point his engine shall cut off, and how he will proportion the "lead" to the "cushion" on the exhaust side, we shall content ourselves with presenting, in Fig. 40, a diagram which will enable him in a simple and ready way to construct the valve and its movement accordingly.

72. The travel of the valve being first determined, describe with it as a diameter a circumference representing the path of the eccentric. Let any

diameter, $f\,k$, of this circle represent the stroke of the piston; lay off f A, the distance to be followed, and draw A e' perpendicular to $f\,k$: describing about f an arc with a radius $f\,l$ equal to the steam lead, draw $e'\,w$ tangent to it, cutting the eccentric's path in e, and also $f\,f'$ parallel to $e\,e'$. Thus far the diagram is identical with Fig. 35, and drawing the line of motion L M through O perpendicular to $e\,e'$, we have $c\,d$ the opening of the steam port, e the position of the eccentric at the beginning of the stroke, $d\,x$ the lead and d O the lap, the sum x O, of the lap and lead, being equal, as we have just seen it should be, to the motion of the valve caused by advancing the eccentric to e from its central position y. And on the exhaust side this same distance, x O, is to be divided between lap and lead. Assuming that, as is found best in practice, the exhaust lead is to be greater than the steam lead, let it be laid off from x to n, and through the latter point draw the chord $h\,h'$ parallel to $e\,e'$.

73. It is then clear that we may make the exhaust port equal to $c\,n$, and that with the lap n O, the port will be opened and closed while the eccentric moves from h to h'. It has moved from h to e before the beginning of the stroke $f\,k$; therefore, if we set off the remainder $e\,c\,h'$ from f to m and draw m A$'$ perpendicular to $f\,k$, we shall find f A$'$, the distance travelled by the piston before the escape is shut off.

Now, in order to construct the valve and seat, let the former be at mid-travel; then, making the exhaust port equal to $c\,n$ and the exhaust lap equal to n O, we have only to add the steam lap $c\,g$ equal to $d\,O$ in order to complete one valve face, the action of which is sufficiently obvious. In proceeding with the seat we must first determine the face of the bridge $n\,p$, separating the port already found from the central one leading to the discharge. We have spoken of the port just laid out as the *exhaust* port; that was simply because it will be opened to the full extent $c\,n$ only on the exhaust side, while on the steam side it will only be opened to the distance $c\,d$. Technically, the two outer ports are called steam ports, and the central

one only is known as the exhaust port. As to the dimension *n p*, it is arbitrary, that is, it depends on practical and physical considerations with which we have nothing to do. It is next to be noted that as the point O of the valve moves to the left as far as *c* to open the port already drawn, it will move to the right as far as B in order to open the other; so that from B to the point *r*, the other edge of the exhaust port, we must set off a distance equal to *c n*, the breadth of the port; after which *r t* is made equal to *p n*, *r s* to *p* O, and the other parts of that end of the valve and seat made similar to those of the other end, as already drawn.

74. Thus constructed, the valve and its seat are of the least length that will admit of an exhaust opening equal to *c n*, which, under the conditions, is possible. But if it be thought unadvisable to make the ports and passages larger than is required by the opening on the steam side, *c d*, it is evident that each of the ports in the seat may be reduced by the distance *d n*, each valve face and the cavity O *s* being shortened to the same extent. The lap remaining unchanged, there would be no difference in the lead or in the time of closing the ports; the only change in the action would be, that the edges of the cavity O *s* in the valve would move beyond the edges *c* and *u* of the ports, to a distance equal to *d n*.

75. So much for the *three-ported* slide-valve—a name derived, as above stated, from the three ports in the valve seat. Now, since the steam enters and leaves the cylinder through the two ports that communicate with it, the third, or exhaust port, can be dispensed with, if some other means are provided for the final release of the steam. Such an arrangement is shown in Fig. 41, and is known as the two-ported, or sometimes as the box, slide-valve. The top of this valve is open, and moves steam-tight in contact with the lower side of the valve-chest cover, an opening through which permits either the entrance or the exit of the steam, generally the former, so that the valve chest is, in fact, an *exhaust chest*, and the *inner* edges of the valves are the steam edges, and in consequence the piston moves in the opposite direction

to that in which the common valve would make it move, the direction of the revolution being the same.

76. The figure represents a full stroke valve, with its movement diagram; in regard to which it need only be remarked, that the radius of the travel circle must of course be equal to the breadth of the port $c\,d$; and since that port is to be fully opened, the port $c\,a$ in the valve must have the same breadth. Also, that the valve being at mid-travel, the distance $g\,i$, from the edge of the opening $g\,h$ in the valve-chest cover, must of course be equal to half the travel, while $i\,l$, the bearing surface, is arbitrary, being determined by practical considerations involved in so packing it, as to secure a steam-tight joint with the least friction. It is plain that whereas the common slide-valve has the steam pressure on the back of it, this form has the advantage of being perfectly balanced. And it is also obvious that it may be arranged to cut off just as the other one can, and with the same disadvantages.

77. The diagram, Fig. 42, illustrates the construction of the valve and the movement, which is precisely the same as that of Fig. 40, except that the steam and exhaust edges are transposed, thus: the circle being described with the given travel, any diameter, $f\,k$, representing the stroke of the piston f A is made equal to the distance to be followed, A e' drawn perpendicular to $f\,k$, and $e'w$ tangent to a circle described about f, with a radius equal to the linear lead, and $f\,f'$ parallel to $e'w$, cutting at a the line of motion L M, which is perpendicular to $e'w$: $a\,b$ is then the breadth of the port, a O the steam lap, and $a\,r$ the steam lead. Assuming either $r\,d$ the exhaust lead, or d O the exhaust lap, draw through d the chord $h\,h'$ parallel to $f\,f'$; set off from f, $f\,b\,m$ equal to $e\,b\,h'$, draw m A$'$ perpendicular to $f\,k$, and A$'$ will be the point of closing the exhaust, $c\,b$, equal to d O, being the exhaust lap. Make $\text{O}\,v = a\,b$, and $v\,u = \text{O}\,s = \frac{1}{2}$ travel, and complete the valve and seat. Also make $g\,i = \frac{1}{2}$ travel, $g\,n$ and $i\,l$ being determined arbitrarily, and the construction is complete.

CHAPTER IV.

OF INDEPENDENT CUT-OFF VALVES.

78. The three-ported valve described in the last chapter may be properly called the "main slide valve," because it governs the ports which communicate directly with the cylinder, and is competent to regulate both the entrance and the exit of the steam, acting well as an expansion valve within certain limits. But the disadvantages already spoken of render it necessary to make use of other arrangements when it is desired to cut off early in the stroke ; some of which, involving the use of slide valves, operated by eccentrics, it is proper to introduce to the reader's notice. Allusion has already been made to the fact that these disadvantages may be avoided by the use of two valves, like the one shown in Fig. 26, one for steam and the other for exhaust, operated by distinct eccentrics, thus enabling the exhaust to continue through the whole stroke, if desired, while the steam valve may be made to cut off at any point. Owing, however, to the fact that the "independent exhaust valve" must necessarily be placed with its face outwards, having the steam pressure upon it from within the cylinder, another difficulty arises from the great additional waste space involved when this arrangement has been adopted; in consequence of which, preference is generally given to what are called "independent cut-off valves."

79. When one of these is employed, the main valve, of the kind previously described, is retained : being usually made to follow full stroke, its function, so far as the steam is concerned, is simply to direct it, while the supply lasts, into the right end of the cylinder.

The duty of the first arrangement of the independent cut-off valve,

which is operated by another eccentric, is solely to regulate the supply of steam to the main valve, admitting it into the steam chest, in which the latter works, at the beginning of each stroke, and cutting it off at the proper time.

80. Under these circumstances it is evident that the ports governed by this valve must be opened and closed twice during each revolution; so that we may adopt either of the two varieties of valve shown respectively in Fig. 10 and Fig. 11.

The general arrangement of the two valves is shown in Fig. 43: the main valve working in a steam chest, upon the back of which is formed the seat of the cut-off valve, which is here shown as a single one of the second variety, Fig. 10.

The action is obvious: the new valve opens and closes the port once in each stroke, thus regulating the supply of steam, while the main valve controls its distribution, and, at the same time, attends to its release after its work is done. And since it cannot admit steam to the cylinder when there is none to admit, it may of course always be made so as to follow through nearly or quite the whole stroke, thus leaving the exhaust free and undisturbed. And the cut-off valve, being operated by a separate eccentric, may, when desired, be thrown out of gear, leaving its ports open, so that in cases of emergency the engine may be worked at full stroke. Lead may also be given to this valve independently; and abstractly it would seem that it ought to be set so as to open a little before the main valve, inasmuch as the valve chest has first to be filled with steam.

81. The action of this form of valve, in respect to the manner in which it opens and closes the port, is identical with that shown in Fig. 19, as already explained; consequently, since this again is precisely that of the steam side of the three-ported valve, discussed in the preceding chapter, the diagram, Fig. 35, shows the method of constructing this valve and its movement, so as to cut off at any required point with any assumed lead. In Fig.

43 we have shown the cut-off valve seat with only one port, as illustrating the abstract principle only of its arrangement and operation in connection with the main valve. In practice, however, it is usual to connect two or more valves together, and to provide the seat with a corresponding number of ports. Since the valve has no cavity in it, and in fact consists simply of a plate in which a number of these ports are cut, its appearance under these circumstances sufficiently justifies the name "gridiron valve," by which it is frequently called.

82. The object of increasing the number of ports is to increase the area of the steam supply. But it may be said, that instead of adding another valve and port, the area might be doubled by making one port of twice the breadth. This is true; but in that case the breadth and travel of the valve must also be doubled, whereas in adding another valve and port the travel need not be increased. Since in each case the *valve face*, or bearing surface, is doubled, it is evident that the latter expedient involves only half the friction of the other; of itself a sufficient reason for its adoption. But this is not all, for the former requires the length of the valve chest to be doubled, since the travel and valve-face are both doubled.

83. Space is saved in this direction by the other plan, thus: The whole traverse of a single valve would be its breadth plus its travel; if we add another valve and port (which as shown in Chap. 1 are together equal to the travel), the whole traverse will be the breadth plus twice the travel; while, if we double everything, we should have *twice* the breadth plus twice the travel. By increasing the number of the ports, then, without changing the travel, instead of increasing their size and the travel too, we shall find that although every port added will make the "gridiron" so much longer than the corresponding single valve would be, yet the traverse or length of the valve seat will be shorter by just the breadth of each additional valve face, while the friction will be reduced just as many times as the number is increased.

84. Figs. 44 and 45 illustrate sufficiently the method of constructing this valve and its movement, to cut off at a given point, with or without lead; the similarity to Fig. 35 being so great that no explanation is required. It is, however, to be observed that as the edge b will move to the right as far as g, the distance $f\,g$ between the ports cannot be diminished, because the valve face $a\,b$ would obstruct the port $g\,h$, in moving to the right, and in moving to the left the edge c would pass beyond f, partially covering the port $i\,f$; beside which, the opening $b\,c$ would be less than the port $g\,h$; so that although the cutting off would be correctly performed, the steam supply would be interfered with. The valve, then, is of the least length that will at once utilize the whole travel, give the full steam supply, and cut off at the given point; but evidently the distances $f\,g$, $b\,c$ may be equally increased to any extent without affecting the action. If, again, other ports be added, it would not be essential that the spaces between them should be equal; but since nothing could be gained by making them otherwise, we may confine ourselves to the consideration of valves whose ports are equidistant.

85. Let it now be required to adapt a valve to a seat already made. If the ports are to be fully opened, it is evident that the diagram when completed must resemble Fig. 45, if lead is to be given, or Fig 44, if not. In either case the travel is equal to the sum of the breadth of a port and the distance to the next, as $i\,f$ plus $f\,g$; and the point of cutting off is found by a reversal of the process of constructing the diagram, first drawing the chords $k\,k'$, $e\,e'$, through the edges f and b of the port and the valve respectively, the latter being placed over the seat with the required lead, and then letting fall e' A perpendicular to the diameter $k\,l$, which represents the stroke of the piston: l A will be the distance followed, and e the position of the eccentric at the beginning of the stroke. If there be no lead, it is obvious that e will coincide with l, as in Fig. 44.

86. But again, after both the valve and the seat are made, it may be

desired to change the point of cutting off. And within certain limits this is possible, if proper changes are made in the travel and in the angular position of the eccentric.

This will be clear from an examination of Fig. 46. The valve being just on the point of opening, the indefinite lines, *x y*, *w v*, are drawn perpendicular to L M, the line of motion, through the edges *m*, *n*.

Let the eccentric be at this time at any point *e* of the line *x y*, below L M; and let it revolve in the direction indicated by the arrow, about a centre in the line L M. From the previous discussion of the action of the valve, we know that at the end of a half revolution the eccentric must be found in the line *w v*; consequently, if we set up *n k* equal to *e m*, and join *k e*, this last line will be the diameter of the circle described by the eccentric, and its intersection with L M will be its centre; and it is clear that *k e bisects m n* in O. Now had we originally placed the eccentric at *f* instead of *e*, it would after the half revolution have been found at *l*, *l n* being equal to *f m*; and *f l*, the diameter of the eccentric's path in that case, would also pass through O. It appears, then, that about O, the middle point of *m n*, we may describe any circle cutting the lines *x y*, *w v*, and consider it the eccentric's path. In this figure, as in the two preceding ones, *k e* is assumed equal to *a p*; when this is done, the edge *m* moving to the left as far as *a*, the port will be fully opened; and drawing *e′* A perpendicular to *k e*, we have *e* A the distance followed.

When the travel is assumed equal to *f l*, it is evident, not only that the port will only be opened to the distance *b n*, but that the angle *l* O *l′* being less than the angle *k* O *k′* in the first circle, the port will be closed earlier in the stroke than before, the new point of cutting off being found in the same manner, by drawing a perpendicular from *f′* to the diameter *f l*.

87. If we make the travel equal to *n m*, the port will not be opened at all; but if we are prepared to sacrifice the steam supply, we can by approaching this limit cut off as early in the stroke as we please. If we go

beyond the limit $a\ p$, making the radius of the circle greater than O a, evidently the edge p will go beyond n to the left, to a distance equal to the difference of the radii, thus obstructing the port. The effect of increasing the travel is of course to lengthen the time of admission; but on account of this interference with the steam supply, it is clearly injudicious to make the travel much greater than $a\ p$, the distance between the corresponding edges of two adjacent ports; as, indeed, should the radius be made equal to O $a + a\ n$, the edge p would move to the left so far as to coincide with a, so that this port $a\ n$ would be entirely closed by its neighbor's valve-face; and whatever the number of ports, this would obviously happen to all except the one on the extreme right.

88. We see, then, that the point of cutting off can be varied to a certain extent; the next and final question is, how to construct a movement by which a given valve may be made to cut off at any point, assumed within the limits just ascertained. The *angular* position of the eccentric, when there is no lead, is the same for any given point of cutting off, whatever the travel, or, in other words, whatever the scale of the diagram, as was explained in connection with Fig. 22; and it would be equally true when lead is given, if it were measured by the angular advance of the eccentric. But this is not the case in practice; the usual form of expression being to speak of a valve as "set with one-eighth of an inch lead," or whatever may be the linear measure of the opening of the port at the beginning of the stroke.

89. Evidently the angle through which the eccentric must be advanced to move the valve so far, will vary with the travel and with its original angular position. When the travel and the point of cutting off are given, the diagram, Fig. 35, enables us to determine the position of the eccentric when the linear lead also is fixed; but it is perfectly clear that we could not determine the precise effect of the lead if the diameter of the eccentric's orbit were not known. It is therefore impossible to construct with absolute precision a movement by which a given valve shall be made to cut off at

a certain point if a definite linear lead be insisted on. But, as before remarked, the lead is usually so small that its effects upon the time of closing need not be taken into account; we can therefore make an approximation sufficiently close for all practical purposes in the following manner.

90. First determine, by means of a diagram, Fig. 47, the angular position of the eccentric, on the supposition that the engine is to follow the given distance e A without lead. Then, placing the valve, Fig. 48, as just opening, bisect $n\,m$ in O, and draw the lines $x\,y$ and $w\,v$ as in Fig. 46; make the angle l O M equal to the angle e O M in Fig. 47, and draw $l\,p$, cutting $x\,y$ and $w\,v$ in e and k respectively; $k\,e$ will be the diameter of the eccentric's path, and e its position at the beginning of the stroke, and the valve will open the ports to the distance $b\,n$, closing them at the given point in the stroke. Now give the required lead, the effect of which will be to diminish the distance followed; ascertain the extent of this diminution, as in Fig. 45, and adding it to the original distance e A used in Fig. 47, make a new diagram, giving a different angle, which being laid off instead of l O M on Fig. 48, will give a new travel and a different opening of the ports. The engine now follows too far; but when the lead is given, the distance followed will be reduced to very nearly the limit originally fixed.

91. Now, as above remarked, the functions of the independent cut-off valve may be fulfilled by the third variety shown in Fig. 11, just as well as by the one we have just been discussing—perhaps in some cases and in some respects better. The general nature of its action having been explained in connection with Figs. 16 and 17, the first question that arises in considering its movement as adapted to this special duty, is how to determine the point of cutting off.

Fig. 49 represents a valve precisely like that shown in Fig. 16; and it is evident that if $e\,k$ be the stroke of the piston, a perpendicular let fall upon it from e' will give A the point of cutting off.

Had the travel and the point of closing been given, we would simply

reverse this process, setting off e A the distance to be followed, and erecting A e' in order to find the chord $e\ e'$, which is parallel to the line of motion, and equal in length to twice the breadth of the port; e will be the position of the eccentric, the direction of the rotation being indicated by the arrow; though it is obvious that if the direction were reversed, the valve would operate precisely as it now does, if at the same time the eccentric were placed at l instead of e, when the stroke begins.

92. The effect upon the action, caused by the introduction of lead, is illustrated by Fig. 50.

An arc being described, as shown, about e as a centre, with a radius equal to the linear lead, a line $r\ w$ drawn tangent to it and perpendicular to L M, determines by its intersection with the circumference $k\ l\ e\ e'$ the new position f of the eccentric at the beginning of the stroke, after which it must pass through the remaining arc $f\ e'$ in order to close the port. If $f f'$ be drawn parallel to $e\ e'$, $e\ f$ will be equal $e'\ f'$, and consequently $e f'$ will be equal to $f e'$, so that a perpendicular from f' to the line $e\ k$ will determine A′ the new point of cutting off.

It is to be remarked that since $e f$ is equal to $e' f'$, $f f'$ parallel to $e\ e'$, and $r\ w$ to $k\ e'$, this last line will, if produced, be tangent to an arc described about f' with a radius equal to that described about e, as explained above.

93. Therefore, if with a given travel it be required to construct a valve which with a stated lead shall close the port at a definite point in the stroke, we proceed as follows. Letting any diameter $e\ k$ represent the stroke of the piston, lay off from e the distance e A′, through which it is required to follow; erect A′f' perpendicular to $e\ k$, and with a radius equal to the linear lead describe an arc about f', and draw $k\ s$ tangent to it; $e'\ e$ will be the *chord of action*, parallel to which draw L M the line of motion, and the chord $f' f$; $c\ d$ will be the breadth of the port, f the position of the eccentric at the beginning of the stroke, the position of the edge a at that time being determined by the line $f\ w$ perpendicular to L M. In regard to the lap of this

valve, or the breadth of the valve-faces $a\,m$, $b\,n$, it was found in Chapter I. that it is abstractly sufficient to make it equal to half the travel, as shown in Figs. 49 and 50. Since, however, in that case the edges m and n, at the extreme points of the travel coincide with d and c respectively, it is necessary in practice to make these faces a little wider, in order to make sure that there shall be no leakage at those instants.

94. Now, plainly there is no reason why any desired number of these valves should not be attached to each other; nor yet why the valve-face $a\,m$ should not perform the same offices for a port to the right of it that the face $b\,n$ does for the port $c\,d$; and this is the case in the arrangement shown in Fig. 51, another port and face being added to the valve; a process which may be continued until this "gridiron" has as many bars as we choose; the same lack of sufficient reason to do otherwise leading us to suppose them, as in the case of the former one, to be made, as well as the ports, of uniform size.

95. It may be remarked that although the port $a\,b$ in the valve and the one $c\,d$ in the seat have been made of the same breadth, each being equal to half the chord of action $e\,e'$, Fig. 49, it is not *necessary* that this should be so; the sum of the two being equal to this chord, either one may be made wider than the other. This is illustrated by Figs. 52 and 53; from which it is seen at a glance that the port in either case, as in Fig. 49, is opened and closed by the movement of the eccentric from e to e', so that the point of cutting off, A, is the same in all. In Fig. 49, each valve-face, $a\,m$, $b\,n$, is equal to half the travel; it is evident that in Fig. 52, each one can be reduced as much as the port $a\,b$ is increased, thus shortening the whole valve by that amount; while in Fig. 53, for the converse reason, the whole valve is lengthened as much as $a\,b$ is reduced. But since in these two arrangements the steam supply is reduced, and a part of the travel wasted by carrying a wide port over a narrower one, or a narrow port over a wide one, these modifications are of no practical utility, and will therefore receive no further consideration.

96. Now, supposing, as before, a valve-seat to be made, Fig. 51 shows how a valve may be adapted to it, in such a manner as fully to open the ports and utilize the travel, and how the point of cutting off is found. The ports in the valve, as well as the spaces between them, being made to correspond with those in the seat, and the valve placed in the position shown, the eccentric's orbit is described, for the practical reason already mentioned, with a radius a little less than the breadth of one of the valve faces, and the diagram of the movement constructed in the manner above explained: the effect of giving lead being afterward ascertained as in Fig. 50.

97. As in the case of the other gridiron valve, so with this, the point of cutting off may be varied by changing the travel and the angular position of the eccentric; but since, in order to close the port in the seat, the one in the valve must pass entirely across it, the area of the steam supply will not be affected by these changes. This is illustrated by Fig. 54, the valve being placed over the seat in the position shown, and lines perpendicular to L M, as $x\ y$, $w\ v$, drawn through the edges a and c respectively, it is evident that we may assume any circle cutting these lines, described about the centre O in the line L M, as the path of the eccentric. There being no lead, it is clear that if we assume the travel equal to $e\ k$, the eccentric must move through the arc $e\ e'$ to close the port; if it be made equal to $f\ m$, then the eccentric must describe the arc $f\ f'$ before cutting off. The angle e O e' is evidently greater than the angle f O f'; whence we see that the less the travel, the farther the engine will follow. In fact, had we assumed the travel equal to twice the breadth of the port, as shown by the smallest circle, it is plain that the port would not be closed till the end of the stroke; so that in order to cut off at all, we must keep outside of that limit; and we have already seen that the radius of the eccentric's orbit must be a little less than one of the valve-faces.

98. In constructing a movement which shall operate a given valve so as with a definite lead to cut off at any point within the limits thus imposed,

we are confronted with the same difficulty as with the other valve, that is, the impossibility of ascertaining the effect of a fixed linear lead unless the travel is known. The method of approximating to the required result is precisely like that adopted in the case of the previous valve, first ascertaining by a diagram, Fig. 55, the angular position of the eccentric, assuming that there is no lead; then drawing the lines $x\ y$, $w\ v$, Fig. 56, make the angle p O M equal to e O M of Fig. 55, and draw $p\ r$, giving the diameter sought by its intersections with $x\ y$ and $w\ v$. The valve will with this movement cut off at the required point A, with no lead; and the approximate correction is made as before described, by first finding how much sooner it will cut off when the stated lead is given; making a new diagram in which it shall cut off so much *later*, and finally substituting the new angle thus found for p O M in Fig. 56, ascertain the new travel, and the result of the lead, as in Fig. 50, which will be found to agree very nearly with the conditions of the problem as originally enunciated.

99. The contrast between these two valve movements will be perhaps more clearly illustrated by the two diagrams, Figs. 57 and 58. The former contains all the elements of the action of a valve of each kind, arranged to cut off at half stroke. L M being the line of motion, and the arrow indicating the direction of the revolution, let e be the initial position of an eccentric operating a valve of the kind first discussed; $a\ b$ will be the opening of its port, $e f$ its chord of action, and e O the distance followed, $e\ h$ representing the stroke. Let a valve of the other kind be operated by an eccentric which at the beginning of the stroke is at g; its port will be O c, its chord of action $g\ e$, and its point of cutting off will be O in the stroke $g f$.

100. In comparing these movements, two points make themselves conspicuous. The first is, that the port $a\ b$ is much smaller than O c; it will presently be shown that it is always smaller, and that the difference will be greater the earlier the valves cut off. The other is, that at the present point of cutting off, the two valves at the instant of closing are moving with the

same velocity; for the angles L O f, L O e, which the *lever arm* of the eccentric at that time makes with the line of motion, are equal. If it is required to cut off earlier in the stroke, the chords of action, ef, $g\,e$, must be diminished; if later, they must be increased. In the former case, the angle L Of will be diminished, and L O e increased; so that at the instant of closing the perforated form of valve would be moving more rapidly than the solid; the reverse being true if the engine follows more than half stroke.

101. In Fig. 58, we have the movements of the two forms, with the ports each equal to one-fourth the travel; when we see that, although the ports are closed by motions of the same rapidity, the solid valve admits steam through three-fourths of the stroke $e\,h$, while the perforated one cuts off at one-fourth the stroke gf.

Now, in Fig. 59, let L M be the line of motion of a perforated valve, and L′M′, perpendicular to it, that of a solid one, the two being arranged to cut off at the same point; under these circumstances their chords of action will be identical, since one is parallel and the other perpendicular to the line of motion of its valve. The direction of the rotation being indicated by the arrow, and e being the initial position of the eccentric, $e\,e'$ is the chord of action, and e A the distance followed, here assumed equal to one-third the stroke $e\,k$; also, $e\,b$ is the breadth of the port of the perforated valve, and $a\,b$ that of the port of the solid one. It will be seen at a glance that in order to follow farther, the eccentric must at the beginning of the stroke be placed nearer r; if it were placed at r, the engine would follow full stroke, $a\ b$ would coincide with a O, and $e\,b$ with r O; making the ports in that case each equal to half the travel; and evidently they are continually approaching this equality as e recedes toward r. But whatever position e may occupy between a and r, there always exists the triangle O b e, right angled at b; whence we have

$\overline{b\ e}^2 = \overline{O\ e}^2 - \overline{O\ b}^2 = (O\ e + O\ b) \times (O\ e - O\ b)$: but $a\ b = O\ e - O\ b \therefore \overline{a\,b}^2 = (O\ e - O\ b) \times (O\ e - O\ b)$: and, dividing the first equation by

the second, and cancelling the common factor in the second members, we have, finally, $\frac{\overline{b\,e}^2}{\overline{a\,b}^2}=\frac{O\,e+O\,b}{O\,e-O\,b}$; thus showing that, as above remarked, $a\,b$, the port of the solid valve, is always less than $b\,e$, the port of the perforated one, the travel and the point of cutting off being the same in both cases.

This diagram also forcibly illustrates the difference between the two forms in respect to the speed at the time of closing; for $e'\,O$ being the *lever arm* of the eccentric at that instant, it is clear that $b\,O$ will represent the velocity of the perforated, and $e'\,b$ that of the solid valve.

102. It is proper to remark here, that although we have for uniformity's sake assumed the direction of the rotation to be against the clock, this is a matter of perfect indifference, as by reference to Fig. 44 it will be seen that the contrary rotation would operate the valve with precisely the same effect, if the initial position of the eccentric were changed from e to e'; and a glance at Fig. 49 will show that the same will be true of the perforated valve there shown if the eccentric be placed at l instead of at e, a point to which we call attention in this place as having a bearing upon the arrangement of cut-off valve, which is next to be described.

103. Having discussed in all essential features the action of the independent slide cut-off valves whose seats are fixed on the back of the main valve chest, it is next to be remarked that it is the motion of the valve in relation to the seat which controls the ports; so that if the whole seat, instead of being stationary, were to move, it would not affect the result in the slightest degree, so long as the valve moved properly upon it over the ports.

It is also to be noted that if the three-ported slide valve be extended, so as to have ports formed in its substance beyond the steam edge, these ports if open would, of course, admit steam to the cylinder just as before; but if valves be placed over these ports and properly actuated, they may by thus sliding on the back of the main valve, which then becomes a movable valve

seat such as we have just alluded to, be made to cut off the steam at any point.

104. We have thus a new combination of the "main slide and independent cut-off," the whole general arrangement of which is depicted in Fig. 60, and requires no further explanation; it remains now to construct a movement by which the upper valve may be correctly moved in connection with the lower one. Were we at liberty to suppose the main valve to carry with it the bearings of an eccentric revolving in either direction at the same rate as the one by which it is itself operated, the problem would be already solved. This, however, is clearly out of the question; but a little reflection will lead us to the consideration, that if two slotted cross-heads, having their lines of motion parallel, are actuated by two concentric cranks of different radii, the extreme movement of one must be greater than that of the other in both directions; and if one of them be attached to a piece which moves freely upon that to which the other is connected, the first piece must necessarily slide back and forth upon the other; let us then examine the nature and relations of the movements thus caused.

105. Fig. 61 may serve a purpose in aiding to form a clear conception of the relations of the moving parts. It represents a valve, $m\,n$, sliding on a face L′ M′; to it is attached a piece A A, behind which is a crank, O c, whose pin c works in and projects through a slot in A A, and in front of the latter, it has rigidly secured to it the extension $c\,d$, thus forming a second crank O d; and the pin d of this crank plays in a slot in a piece B B, which moves in guides attached to A A, both slots being perpendicular to L′ M′; a second valve, $k\,l$, is secured to B B, and controls a port in the first valve $m\,n$. It is obvious at a glance that as the two cranks revolve together, the two pins must after a quarter revolution lie in the same vertical line $x\,y$; so that the piece A A will have moved to the left through the distance c O, and B B through the distance d O; the latter must, therefore, have moved over the former, sliding in the guides $g\,g$, and carrying the valve $k\,l$ to the left over

its port, through the distance $d\,c$; which will evidently be repeated during the next quarter of the revolution, after which, the crank pins having reached the points c' d' respectively, the two valves will return, and these movements will take place in the reverse order and direction.

106. In order to illustrate more clearly the nature and relation of the two movements, the parts are shown in the diagram, Fig. 62, in six different positions in the revolution; the slots, being always vertical, are indicated by short vertical lines through the various positions of the centres c and d.

Now, since O $c\,d$ is a straight line, $c\,d$ will always make the same angle with a vertical line that O c does; and since the slot in the piece A A is here represented by a vertical line always drawn through c, and $c\,d$ is constant, it follows that with respect to that slot, the point d moves precisely as it would, were the slot to remain stationary, and d to rotate around c, in the same direction and in the same time that it now revolves around O; thus, it is evident that in moving from c to c', a change has taken place in the relative position of the slots $a\,b$, $g\,h$, which have moved to $a'\,b'$, $g'\,h'$ respectively; and that had c remained stationary, the slot $g\,h$ would have been made to approach $a\,b$ to exactly the same extent, by causing d to rotate around c through the same angle $c\,\mathrm{O}\,c'$, as indicated by the dotted lines; and the diagram will enable the reader to trace the motions during the remainder of the revolution without farther explanation.

107. For the sake of simplicity, we made $c\,d$ a prolongation of O c; but this is not necessary; it may make any angle with O c, the only result being that it will at all times make with the vertical line an angle so much greater or less than it now does. The vertical line always passing through c, and $c\,d$ being constant, d in effect rotates around c, as shown in Fig. 63, and causes the valves to slide upon each other, as before; only, of course, the relative positions of the valves, at the same points in the revolution of c, will be different.

Now, the transverse motion of the crank pins in respect to the lines of

motion of the valves being accommodated by the slots in the pieces A A and B B, and the point *d* virtually revolving about *c* as a centre, we have a combination of movements precisely equivalent to that which would result from the revolution of an eccentric in bearings fixed to the main valve, itself operated by another eccentric revolving at the same rate and in the same direction ; and it is next required to construct the movements in such a manner as to meet the requirements of the engine. In order to show how this may be done, we will first refer to Fig. 60, in which the main valve is to follow full stroke ; and let it be required to make the independent valve cut off at half stroke, no lead being given to either.

108. Now, the valves having the relative positions shown, if they both move to the left, but the upper one faster than the lower, steam will be admitted to the cylinder through the ports *l m*, *b a*, on the right. It is to be noted, that it makes no difference, whether the port *i k* in the other end of the main valve, be opened at the same time, as it will in the arrangement shown in the figure, or whether the valve-face *p q* be extended to the right (and, of course, *o n* to the left, at the same time); for that matter, the whole distance *p o* may be occupied by one solid valve. For evidently the steam can only fill the passage *i k*, *f e*, in the main valve, which by moving to the left prevents its entrance into the cylinder. But it *is* essential, evidently, that after a half revolution, the main valve having then returned into its present position, the independent one should have moved so much farther to the right as to have its edge *p* coincide with *i*, in order to admit steam to the port *d e*, as soon as the main valve opens it by moving to the right from its central position for the return stroke.

109. In effect, therefore, the operation of this valve, *p o*, is identical with that of the one shown in Fig. 43 ; for the whole distance from *i* to *m* may be considered as one long port, opened from the right-hand edge for one stroke, and from the left-hand edge for the other, though not for the full length : the valve-seat moves, to be sure and the valve-chest into which it admits steam

is now reduced to the dimensions of one of the passages in the main valve; but the cut-off valve itself, and its movement in relation to its seat, are precisely similar to those illustrated in Figs. 14 and 15.

In order then to construct this movement, supposing the valves and ports to be given as in Fig. 60, we first describe the circle $c\, c^1\, c^2\, c^3$, Fig. 64, being the orbit of the main eccentric, whose radius is therefore in the present case equal to the breadth of the port $a\, b$; and the horizontal line L M being the line of motion, the eccentric at the beginning of the stroke will be at c in the vertical line $x\, y$, through O the centre of revolution. Next, by the process described in connection with Figs. 47 and 48, construct the movement of the cut-off valve, as though the seat were fixed; and about c as a centre, describe a circle with a diameter equal to the travel found to be requisite for the cut-off valve, and draw the lever-arm $c\, d$ of its eccentric in its proper angular position, as found in the separate diagram like Fig. 47; d O will be the lever-arm of an eccentric revolving, with the one whose *lever-arm* is c O, about O as a centre, which will give the cut-off valve its proper motion with regard to the main valve, as shown in the figure.

110. Nothing has been said of any lap upon the main valve, nor of any lead given to either; nor is it necessary for us to illustrate by a diagram the process of constructing the movement if these elements are introduced, because the diagrams of the main and the cut-off valve movements are in any case constructed separately, and then combined as just shown. Consequently, were lead given to both valves in Fig. 64, we should only have c a little to the left of its present position, and $d\, c\, s$, the angle made by $d\, c$ with a horizontal line, would be a little less.

We have in the diagram endeavored to illustrate the action of the eccentric d, by introducing in each of the four positions in which the eccentrics are shown, a smaller diagram, showing the virtual revolution of d about c, and its action upon a valve and port; the ones in the positions c, c^1, corresponding to the valve $n\, o$ and port $l\, m$ of Fig. 60; those at c^2 and c^3 corresponding to $p\, q$, $i\, k$; it is hardly necessary to add that if lead were introduced

the positions of these valves would be changed, leaving the ports a little open at c and c^2, and overlapping them a little in the positions c^1 and c^3.

111. This combination enables us to vary the point of cutting off, without touching the eccentrics at all, and if desired, even while the engine is in motion. The manner of accomplishing this will be readily understood, when we reflect upon the circumstance that in order to follow full stroke, the eccentric at the beginning of the stroke is placed in its central position in regard to the travel, as at h, Fig. 18 ; if it be advanced beyond that point, as to e, Fig. 32, with no change in either valve or port, the distance $d\ e$, to which the valve is thus moved beyond mid-travel, will be lead, and the port will be closed before the end of the stroke, as explained in connection with that figure ; we may close the opening of the port, either by making the port itself narrower, as in Fig. 19, or by adding to the breadth of the valve, as in Fig. 20, which we have seen amounts to the same thing in effect ; this addition will be "lap" when the valve is at mid-travel. As stated in the last chapter, on the steam side of the main valve we are compelled to do this if the angular advance be considerable, since great steam lead is inadmissible, while on the exhaust side we may add much or little lap, and retain as much of the lead as we choose.

112. And in this case we have the same option : because our cut-off valve admits steam only into ports in the main valve, and if that have the right lead, it makes no difference how much that of the independent valve is varied. The sum of the lap and lead, as we have seen, is equal to the distance of the initial position of the valve from its central position ; in the diagram, Fig. 64, we constructed the movement, and have shown the valve, as having all lap and no lead ; under which circumstances the cutting off takes place at the given point ; if we now give lead by reducing the lap, the port will be opened sooner, but closed later. And this we can do ; for it has been pointed out already that the outer edges, p and o, of the cut-off valve in Fig. 60, are the ones which do the work, it being useless to open the ports on the edges k and l.

113. If, then, the two valves, $p\ q$ and $n\ o$, are connected with each other by a right and left hand screw, they may be made to approach or recede from each other at pleasure ; and since they will move equally in respect to the central point, the lap of the edges o and p will be reduced or increased to the same extent, so that the cutting off will take place at the same point in each stroke. The same means of varying the point of cutting off could also be used when a valve of this kind is placed on the back of the main valve chest, as in Fig. 43.

114. It is plain that if the ports on the back of the main valve are properly arranged, a perforated cut-off valve might be employed ; and in Fig. 65 one is shown in combination with a full stroke two-ported box valve. The diagram of the combined movements is given in Fig. 66, as showing the points of difference and of resemblance between it and that of the other combination, shown in Fig. 64 ; but it is unnecessary to say anything in the way of detailed explanation of its construction, which depends upon the same principles, and is conducted in substantially the same manner as that of the movement of the solid valve, just described.

115. It is, however, to be observed that the inner edges of the cut-off ports, in Fig. 60, may be made the opening edges, just as well as the outside ones ; if, for instance, at the beginning of a stroke to the left, the edge n of the valve is placed coincident with the edge l of the port, it will appear that this state of things is precisely that shown in the lower position, c^2, of the diagram Fig. 64 ; from which it is evident that the initial position of the cut-off eccentric must under these circumstances be changed from d to d'' ; and a movement thus constructed is shown in Fig. 67.

Again, since with the perforated valve it can make no difference whether the opening moves over the port in one direction or the other, an examination of Fig. 66 will show that in that combination, too, the position of the cut-off eccentric might be changed from d to d'', without affecting the action ; and the movement thus modified is illustrated in the diagram, Fig. 68.

CHAPTER V.

EFFECTS OF THE ANGULAR VIBRATIONS OF THE ECCENTRIC ROD AND MAIN CONNECTING ROD.

116. Thus far, we have adhered strictly to the supposition that the motions imparted by the piston to the crank, and by the eccentric to the valve, have been transmitted in the rectilinear *lines of motion* of the piston and the valve respectively; in other words, that the component parts of the circular movements of the main crank and the eccentric which are transverse to these lines of motion, are so accommodated by "slotted crosshead connections" or their equivalents, that their effect is neutralized.

But in practice this supposition is seldom, if ever, strictly true. There is a radical difficulty with this form of connection as a means of transmitting power, arising from the friction attending its action when near the "dead centres," which practically precludes its use for that purpose; in pumping-engines it is sometimes employed, but mainly for the purpose of limiting the motion of the piston and the valve, the power being transmitted, not through the crank and shaft, but directly from the piston of the engine to that of the pump, the two being connected to the same rod.

117. Since, then, the irregularities of motion, alluded to at the outset in connection with Fig. 4, are always or nearly always to be encountered, it behooves us to inquire into the matter, and see what they amount to.

In doing this, it may be as well to look at one thing at a time—and better that the first should be the more tangible and important. Referring again to Figs. 3 and 4, we see that these perturbations are due to the obliquity of the actual motions of the connecting rod and eccentric rod, hereto-

fore supposed to take place in directions parallel to the lines of motion of the piston and the valve. And a glance at these figures is enough to show that the stroke of the piston being ordinarily much greater than the travel of the valve, the main connecting rod will in the course of the revolution deviate more than the eccentric rod from this supposed parallelism.

118. In the first place, then, the motion of the eccentric being transmitted to the valve as before, let us suppose a main connecting rod of the ordinary form to be introduced, the connections being direct in both cases, as in Figs. 3 and 5; the result of this change can be readily seen by the aid of the skeleton diagram, Fig. 69, in which, $a\,c$ representing the stroke of the piston and $a\,a'$ the length of the connecting rod, the circumference $a'\,b'\,c'\,b''$ will be the path of the main crank, the smaller one $t\,e\,r\,e'$ being that of the eccentric. Now, supposing the piston to be at a, and the main crank at a', the arrow indicating the direction of the revolution, it is clear that e will be the initial position of the eccentric, assuming also that the valve, of the common kind, is to follow full stroke without lead, as in Fig. 29; and it is equally evident that when the piston reaches c, the end of the stroke, the eccentric will be at the proper position e', ready to open the valve for the return stroke.

119. We not only *may*, but *must* give the eccentric the initial position shown, in order that the valve may be opened at the proper times; but the port will not be full open at half stroke as it was originally.

About b, the middle point of the stroke $a\,c$, with a radius $\mathrm{O}\,b = a\,a'$, describe an arc, cutting the path of the main crank in l and m; also about b' or b'', with the same radius, describe an arc cutting L M in p: it will then be seen that while the piston makes the half stroke $a\,b$, the crank moves only through the arc $a'\,l$, instead of the quadrant $a'\,b'$; and when the crank has reached b', the piston will have advanced to p, which is the point in the stroke at which the valve is full open. If we draw $l\,\mathrm{O}$, cutting the eccentric's path in s, lay off from e an arc $e\,s' = t\,s$, and drop the perpendicular $s'\,v$ on L M, it is evident that $\mathrm{O}\,v$ is the extent to which the port is open when the

piston is at half stroke, and $v\,r$ the remaining part of the opening, which will be accomplished while the piston moves from b to p. On the return stroke, of course, the valve is full open when the piston reaches the same point p, or *before* half the stroke is completed.

120. Having alluded above to the connections as being *direct*, it may be as well here to notice the distinction between "direct-acting" and "back-acting" engines. Fig. 3 represents the former—and so does the diagram Fig. 69. It will be observed that the connecting rod, as well as the cylinder, lies to the right of the main shaft; now, by extending the piston rod, it is evident that without moving the cylinder, the connecting rod may be made to lie to the left of the main shaft, as in the diagram Fig. 70 ; and this is the movement of the *back-acting* engine. It is obvious that this diagram and the preceding one are perfectly symmetrical, the stroke and the length of the connecting rod being the same in each : consequently whatever occurs in a stroke from left to right in the first, will occur in one from right to left in the second, and *vice versa.*

121. Nor will the direction of the revolution affect the action in the least : so that either the eccentric may be placed at e' instead of at e, or, as indicated in faint lines in Fig. 70, a rock-shaft and lever may be introduced, by which the motion of the valve, and consequently that of the engine, will be reversed, while the events in the stroke will occur at the same times as before : the vibrations of the rock-shaft arms being neutralized as indicated, by the use of the slotted crosshead connection, before described. It need hardly be remarked that the substitution of the two-ported valve for the three-ported one, will also cause the direction of the revolution to be reversed, unless one of the modifications just mentioned is also introduced, or the steam is admitted into the valve-chest outside the valve.

122. Let us now suppose lead to be given, by advancing the initial position of the eccentric beyond e, as in Fig. 32. (We may remark in passing

that no further notice need be taken of the modification shown in Fig. 33, for securing the admission of steam during the entire stroke when lead is given ; the small amount of expansion caused by the lead comes so far within the limits of utility, that practically a full-stroke valve is understood to mean one like that shown in Fig. 29, the breadth of the port being equal to half the travel.) In order to open the port fully, the eccentric has now, as shown in Fig. 32, to move through an angle less than 90°, by the amount of the angular advance from the central position. For the sake of illustration, let this advance be equal to *l* O *b*′, in Fig. 69, the angle which the crank lacks of describing a quadrant during the first half of the stroke *a c*.

123. The results of this change are exhibited in the diagram, Fig. 71, where, as in our previous ones, the same circle represents the paths of both piston and eccentric. Here, the valve being shown in the initial position, with its edge directly under the eccentric *e*, and the lead angle *b* O *e* being equal to *l* O *b*, the arc *e c*′ is equal to *a*′ *l*, so that the port will be full open when the piston reaches *b*, the middle of the forward stroke. A quarter revolution is required to close it ; and *n* O *n*′ being drawn at right angles to *l* O *l*′, the crank will then have reached *n*. Dropping from this point a perpendicular upon L M, we find *d*′ *c*′, which would be the remainder of the stroke had we retained the infinite connecting rod. But since we have not, we describe about *n*, with a radius equal to the actual finite length *c c*′, an arc intersecting L M at a point *d*, which is the position of the piston at the instant of closing the port : the real distance *d c*, yet to be traversed, being a little *less* than *d*′ *c*′. Since a half revolution is made at each stroke, the lead will be the same for the return stroke as for the forward one, the crank being at *c*′ when the eccentric reaches *e*′. In order to fully open the port, the latter must describe the arc *e*′ *a*′, the former the equal arc *c*′ *l*′, while the piston will move to *p*′. A quarter revolution being again required to close it, the crank at the end of that time will have reached *n*′ : and by the process just described, we find the distance *h a*, the portion of the return stroke yet to be made ; which

is a little *greater* than $h' a'$, the corresponding fraction when the length of the connecting rod is infinite, instead of a little less as in the forward stroke.

124. These results would not be affected by reversing the direction of the revolution : for in order to do that, the initial position of the eccentric need only be changed from e to l' ; and since $c' l' = e\ c'$, the *angular positions* of the eccentric, crank, and connecting rod, with relation to each other and to L M, would vary exactly as before ; what now occurs above the line L M would then take place below it, and *vice versa.* By merely inverting the diagram, it will exhibit the motion of a back-acting engine : showing that what is here true of a forward stroke will then occur in the return stroke, and the contrary.

125. A second line of motion, L′ M′, has been drawn, and on it are marked the points in the stroke at which the events occur when the slotted crosshead is employed, so that the changes due to the substitution of a finite connecting rod may be more readily traced. And they may be thus recapitulated. When there is no lead, the points in the two strokes at which the port is full open, coincide ; in the first arrangement at b the middle of the stroke, but in the second at another point p, whose distance from b depends on the ratio between the length of the crank and that of the connecting rod. Representing the former by R, the latter by C, the triangle $O\,p\,b'$ gives $O\,p = \sqrt{C^2 - R^2}$; and since $O\,b = C$, we have $p\,b = C - \sqrt{C^2 - R^2}$. When lead is given, since the full opening occurs earlier in each stroke, these points no longer coincide, but are separated by a distance which increases when the lead increases.

126. The diameter $a'\,c'$ representing the stroke of the piston in the original arrangement, it is evident from inspection that the points v', w', at which the port is full open in the forward and return strokes respectively, are equidistant from O : so that on the line L′ M′, $v'\,b = b\,w'$; and this equality will always obtain, whatever the lead. But with the finite connecting rod, although, as shown by the similarity and equality of the triangles $l\,v'\,b$, $l'\,w'\,p'$,

we find $p' b = w' v'$, yet $p' p$ and $p b$ are not equal: for the triangle $b' O p$, having the same hypothenuse as the other triangles, has a greater perpendicular, and hence its base $O p$ must be less than $w' p'$ or $v' b$, whence $p' p$ must be less than $p b$. But this inequality, since it can never exceed that between $p c$ and $p a$, will not be great unless the lead is excessive; and the same is evident in respect to the inequality between $c d$ and $h a$, before spoken of.

127. Since in the valve, Fig. 29, all the edges act simultaneously, whatever has been found true of the action on the steam side is equally true in regard to that on the exhaust side; and it is also obvious that these distances $d c$, $h a$, are those traversed by the piston against the pressure of the steam from the valve-chest; for this being admitted at the same time that the exhaust is closed, the "cushioning" is wholly on the lead.

128. These irregularities in the movement are absolutely unavoidable, so long as the ports are each equal to half the travel. But within certain limits the full opening can be made to take place at the same point in each stroke, if it be thought worth while to do so, by making the port at one end of the cylinder wider than that at the other, as shown in Fig. 72. It being required to follow full stroke without lead, neither port can be wider than half the travel; and, b being the middle of the stroke, p, determined as before, is the point in the stroke $c a$ at which the port $e d$, equal to $O a'$, is full open. Make $b r = b p$, and $r r' = p b''$: then $a r$, equal to $c p$, will be traversed by the piston while the crank moves from a' to r'. From b', the initial position of the eccentric for the stroke $a c$, set off $b' r'' = a' r'$, and drop the perpendicular $r'' x$: $O x$ will evidently be the breadth of a port which will be full open when the piston reaches r; $x c'$ being waste motion.

129. However, if the ports are wide enough, and opened at the proper time, these inequalities in either the time or extent of their greatest opening are of very little consequence, especially in a full-stroke engine: for if the area be sufficient to allow a free supply and a free escape, so that the steam

shall neither be "*wire-drawn*" in entering nor choked in departing, it can make no difference whether at any time it be greater or not.

130. Of much more consequence is the effect of the angular vibration of the connecting rod upon the time of *closing* the ports, as affecting the degree of expansion or compression. Were four separate valves used, each operated by its own eccentric, it need hardly be remarked that all the irregularities in the closure could be easily rectified, as it would only be necessary to ascertain the angles through which the crank would move during the given fractions of the stroke in either direction, and construct each valve movement independently upon the data thus obtained.

131. But the results, when only one eccentric is used, will be, perhaps, most readily seen if we first consider the case of a valve intended to cut off at half stroke, which is illustrated in Fig. 73. The chords of action, $e\,e'$, $f\,f'$, ought each to subtend an arc of 90°, and are so drawn, giving the equal ports $c'\,x$ for the forward stroke $a\ c$, and $a'\ y$ for the return stroke. But a quarter of a revolution requires the piston in the forward stroke to move from a to p, and in the return stroke only from c back to p; so that the closure takes place too late in the former and as much too early in the latter, there being, as shown by the positions of the valves, no lead. Now, the ports $c'\,x$, $a'\,y$, may correspond respectively to C, C′, Fig. 29, to $i\,f$, $g\,h$, Fig. 44, or to $l\,m$, $k\ i$, Fig. 60, as we choose to consider them either as leading directly into the cylinder, and controlled by the main slide, or as formed in the back of the main valve or its chest, and controlled by an independent cut-off valve.

132. In either case there is one means of compensating for the inequality of $a\,p$, $c\,p$, or, in other words, of making p virtually the centre of the stroke, which it is proper to mention here.

It must not be overlooked, that the stroke of the piston multiplied by its area, is not the real measure of the cylinder in practice, although it would

be very desirable to have it so. Beside the "clearance" at the ends, the passages which must intervene between the cylinder and the valve-seat, form a very considerable item in the quantity of steam required at each stroke, which must expand after the port is closed.

Now, it is not necessary that the main valve seat should be placed in the centre of the length of the cylinder, as we have shown it, but it may be moved endlong, thus increasing the volume of the passages at one end of the cylinder, and diminishing it at the other.

133. And the area of the piston multiplied by the known distance $p\ b$, gives a definite volume ; and if the valve-seat be moved toward a, so far as to add one-half this volume to the passage at the other end of the cylinder, the quantities of steam admitted for the forward and the return strokes will be equalized.

But since it acts expansively for a greater fraction of the return stroke than of the forward one, it will be necessary, in order to equalize the power developed during the two strokes, to move the valve-seat a little farther, so as to admit a little more steam during the former than during the latter.

134. This equalization is not in all cases necessary or even desirable ; in vertical and inclined engines it is not uncommon to give more lead and to follow farther on the up stroke than on the down stroke, in order to counterbalance the weight and momentum of the piston and its connections. But as as in many cases it *is* desirable, we have mentioned the above as one expedient ; and it remains to consider what will happen if it be not adopted.

135. Now, we can make the valve close the port at the middle of the return stroke, in Fig. 73, thus : make $f'\ g = b''\ m = l\ b'$ (or $f\ g = c'\ m$), draw $g\ v$ perpendicular to L M, and make the port $= a'\ v$. Thus, while the piston moves from c to b, the crank goes from c' to m, and the eccentric from f to g. But the valve will now have a linear lead equal to $v\ y$, on the return stroke, while there is none on the forward stroke. We can also make the

other port close at half stroke, by diminishing the arc $e'\,e$, until it is equal to $a'\,l$, thus reducing the port $c'\,x$, as shown in dotted lines.

Since by this operation the initial position of the eccentric for the return stroke will be changed from f to i, it is plain that in order to make the valve cut off at half stroke, we must now make the arc $i\,k = c'\,m$, thus making the port equal to $a'\,w$, and the lead equal to $w\,z$, there being still no lead on the forward stroke ; and if we give lead on that stroke, it is evident that since the eccentric must be moved still farther ahead, the arcs $f\,i$, $g\,k$, must be also increased, adding still more to the lead on the return stroke.

136. This diagram then shows that the point of cutting off can be made the same in each stroke, but only at the expense of inequality in the lead ; as indeed might have been inferred from the fact that when the finite connecting rod is used, the piston is in the forward stroke always ahead of, and in the return stroke always behind, the position it would have with the infinite one, the two movements agreeing only at the beginning and end of the the stroke. We have selected the half-stroke cut-off for the purpose of illustration, because in this case the angular positions of the connecting rod are more nearly like those in the preceding figures, but evidently the same process will enable us to follow equally through any other fraction of the two strokes.

137. Fig, 74 shows the construction of an independent cut-off valve with the same conditions, viz., that the closure shall take place at the middle of each stroke, there being no lead on the forward one. Having first found the arcs $a'\,l$, $c'\,m$, as before, we make $c'\,e = c'\,e' = \frac{1}{2}\,a'\,l$; draw e O f, and make $f\,a'\,g = c'\,m$; then drawing the perpendiculars $g\,v$, $f\,y$, we have $a'\,v$ for the breadth of the port, $a'\,x$ for that of the valve, and e for the initial position of the eccentric for the forward stroke, to which the given position of the valve corresponds ; as the eccentric advances, the port will be opened from the edge a' to the distance $x\,c'$; on the return stroke the port will be opened from the edge v, and at the beginning of the stroke there will evidently be

a lead equal to $v\ y$, and the port will be fully opened. Had it been required to give a definite linear lead on the forward stroke, it would have been requisite to find the angular position of the eccentric, by a process shown in Fig. 75 ; the angle $e\ o\ f'$ being made equal to a' O l of Fig. 74, describe about e an arc with a radius equal to the given lead, tangent to which draw $f'\ x$; $f\ f'$ will be the chord of action, to which the line of motion L M is perpendicular, giving $a\ b$ the lead assumed, and $a\ c$ the opening of the port. Now, transferring the angle L O e, Fig. 75, to Fig. 74, we will have the angular position of the eccentric under the new condition, and the remaining steps are the same as already described.

138. As has been already intimated, this construction is applicable to both the main and the cut-off valve ; and the valve shown in Fig. 74 may be placed either on the back of the main slide or on the back of its valve-chest.

In the latter case it may be extended into a gridiron form, by adding any desired number of ports to the valve-seat, as $u\ w$, with corresponding valve-faces, the distance $v\ u$ being of course equal to $a'\ x$.

In the former case, the edge a' in the arrangement shown in Fig. 74, corresponds to m, Fig. 60, and the edge v of the former to i of the latter ; the movement of Fig. 74 being combined with that of the main valve in the same way as in Fig. 64.

But since the points e and f are diametrically opposite to each other, the eccentric may be placed at f instead of e at the beginning of the forward stroke, in which case the arrangement of the port and valve at that instant are shown in Fig. 76.

The edges $c'\ v$, now correspond respectively to the edges $l\ k$, Fig. 60 ; and the movements of the main and cut-off valves are combined as in Fig. 67.

139. These processes of equalization are more especially applicable to the independent cut-off valve movements, for the reason already pointed out,

that if the lead of the main valve be right, that of the other is of no consequence, and may be increased or diminished on either stroke or both, without affecting the action, except in so far as a change in the lead affects the point of cutting off. Still, if we are content to have the lead unequal, we can by a similar process construct a movement in which not only the cut-off, but the exhaust closure of the main valve shall be equalized. As an example, let it be required to make a valve which, with a given travel and a stated lead on the forward stroke, shall cut off at five-eighths and close the exhaust at three-fourths of each stroke. In order to avoid confusion, the "skeleton movement" of the connecting rod is given separately in Fig. 77. The construction is as follows:—

140. First, lay off $a\ p$, five-eighths of the forward stroke, and from p with the known length of the connecting rod set off the point l on the circle of the crank-path; about l, with a radius equal to the stated linear lead, describe an arc, to which draw $a'\ w$ tangent as shown, thus determining a chord $a'\ d$, which, it will be seen, corresponds to the chord of action $f\,f'$, in Fig. 75.

Next, the eccentric's orbit in Fig. 78 being of the same diameter as the crank's path in Fig. 77, the arc $f\,f'$ in the latter, bisected at c', is made equal to $a'\ d$ in the former; and an arc being described about f, with the linear lead as radius, N x, tangent to this arc and perpendicular to L M, determines e, the initial position of the eccentric for the forward stroke, $y\ x$ being the assumed lead, $y\ c'$ the opening of the port, and y O the lap, on the steam side for the same stroke.

Now in Fig. 77, make $a\ i$ equal to three-fourths of the forward stroke, and in the same manner as before, find the point q, the arc $a'\ q$ being that through which the eccentric moves, while the piston moves from a to i; make in Fig. 78 $e\ h$ equal to $a'\ q$, and draw $h\ z$ perpendicular to L M; $z\ x$ will be the lead, z O the lap, and $z\ c'$ the opening of the port on the exhaust side for the forward stroke.

141. Now, a half revolution being made at each stroke, e', diametrically opposite to e, will be the position of the eccentric at the beginning of the return stroke ; and making $c\,p'$, Fig. 77, equal to five-eighths of that stroke, we find that while the piston moves so far, the crank describes the arc $c'\,m$, to which then we make $e'\,g$ equal, in Fig. 78, and drawing $e'\,l$, $g\,m$, perpendicular to L M, we have O m the lap, $m\,l$ the lead, and $m\,a'$ the opening of the port on the steam side for the return stroke.

And making $c\,i'$, Fig. 77, equal to three-fourths of the same stroke, we find $c'\,q'$ the arc described by the crank during that part of it ; make $e'\,k$, Fig. 78, equal to this arc, and draw $k\,n$ perpendicular to L M ; O n will be the lap, $n\,l$ the lead, and $n\,a'$ the opening of the port on the exhaust side for the return stroke.

142. By the term "opening of the port," it need hardly be explained, is implied the distance to which the opening edge of the valve moves past that of the port, and as these four valves vary from each other in this particular, it is plain that our two ports cannot be made made to suit them all, in such a way as exactly to utilize all the motion and just open the ports. But this cannot be helped, any more than the inequality of the lead; but whatever the breadth of the ports, if the lap on the two sides be correct, the cut-off and the exhaust closure will take place at the proper times.

143. In the figure, it is assumed that $m\,a'$, the steam opening for the return stroke, (which is very nearly equal to $z\,c'$, the exhaust opening for the forward stroke), is sufficient for all purposes ; and O m being the steam lap for the former, we have only to add $a'\,r =$ O z, the exhaust lap for the latter, and assume $a'\,p$ at pleasure, in order to complete the left-hand part of the valve and seat. The valve being at mid-travel, $r\,t$ must be made equal to O a' + $m\,a'$, that the escape may not be choked when the valve moves to the right : $t\,u$ is made equal to $a'\,p$, the port $u\,v$ to $m\,a'$, the steam lap $v\,w$ to O y, and the exhaust lap $u\,s$ to O n, which finishes the right-hand part of the arrange-

ment, and gives us a valve which will do its work under the stated conditions.

We have drawn the three-ported valve, because it is the form most commonly used; but evidently the two-ported one could have been constructed under the same conditions just as readily as this.

144. If the independent cut-off valve be of the third, or perforated variety, the equalization of its action is readily effected, but of course at the expense of destroying the equality of the lead. The mode of proceeding will be readily understood by the aid of Fig. 79, which represents such a valve arranged to cut off at half stroke in both directions. The arc $e\,e'$, bisected at b', being made equal to $a'\,l$, we have e, the position of the eccentric at the beginning of the forward stroke; and the perpendiculars $e\,d$, $e'\,n$, determine the closing edges d and n of the valve and seat respectively for that stroke, it being assumed that there is to be no lead on the return stroke, at the beginning of which the eccentric will be at f, the edge d coinciding with n.

Now, making $f\,f' = c'\,m$, and drawing $f'\,h$ parallel to L M, it is clear that in order to open and close the port at the required point, the valve must move through a distance equal to $h\,f'$: and bisecting this at g, we set off the distance $h\,g$ from n to r for the port in the seat, and from d to k for that in the valve; and the valve being drawn in the proper position for the beginning of the forward stroke, it is evident that it will have a lead equal to twice $p\,g$, or to $i\,f'$ on this stroke, although there is none on the other.

145. Had it been stipulated that a definite linear lead should be given on the return stroke, it is to be observed that the closing edge d for the forward stroke, is the opening edge for the other, and that since e and f are 180° apart, if d be moved forward by advancing e, it will after a half revolution have moved past n to the same distance. In other words, we proceed exactly as though a definite lead were to be given on the forward stroke; and since after the beginning of this stroke the eccentric is to move through the arc $a'\,l$, (or its equal $e\,e'$,) before closing the port, we find the line of motion as

follows: About e', Fig. 80, with a radius equal to the given lead, describe an arc, tangent to which, as shown, draw $f\,x$ from the extremity f of the diameter $e\,O\,f$; and perpendicular to $f\,x$ draw the line of motion L O M: $e'\,i$ and $e\,d$, perpendicular to L M, determine as before the edges d and n of the ports in the valve and the seat respectively, the valve being of course placed in its proper position at the beginning of the forward stroke. At the beginning of the return stroke the eccentric is at f; and making $f\,f' = c'\,m$, draw $f'\,h$ parallel to L M; f' is the position of the eccentric when the port closes, and it evidently begins to open when the eccentric reaches i; therefore, $h\,f'$ is the whole distance traversed by the valve in opening and closing the port, the breadth of which is, consequently, $n\,r = h\,g = \frac{1}{2}\,h\,f'$; and setting back $d\,k = n\,r$, we find $r\,k$ the lead on the forward stroke. This mode of procedure, it need hardly be remarked, will be found equally applicable if any other point of cutting off be selected.

146. These irregularities and inequalities in the movement, which result from the angular "vibration" of the main connecting rod, are the most prominent of the ordinary variations from the normal conditions which obtain when the slotted crosshead connections are used.

But there are others arising from the use of a finite eccentric rod; similar in kind, because, as seen from Fig. 3, the valve movement is precisely like the piston movement; but less in degree, because the eccentric rod is usually much longer in proportion to the travel than the connecting rod is in proportion to the stroke.

The former were of such magnitude and importance as to require separate consideration; this is hardly the case with the latter, more particularly as it is very improbable that in practice a slotted crosshead would be used for the piston connection in combination with a finite eccentric rod, the effects of which, therefore, we need only examine with reference to the ordinary construction shown in Fig. 3.

147. The shorter the rod in proportion to the travel, the more con-

spicuous these effects will be; and for the purposes of illustration, it will be most convenient to suppose the ratio to be the same as that between the main connecting rod and the piston. Under these circumstances, the diagram Fig. 71 may represent both the piston movement and the movement of a full-stroke valve. Supposing the latter to have no lead, b' at the beginning of the forward stroke will be the position of the eccentric, and p that of the valve, which is thus drawn ahead of the normal or central position it would have occupied had the eccentric rod been infinite, or always parallel to L M, as shown at $b'x$.

148. It is therefore evident that the full opening of the port will take place as before when the piston is at p in either stroke; but since at the beginning of either the valve is at p, the extent of the opening will be only equal to $p\,c$ on the forward stroke, but equal to $p\,a$ on the return stroke; so that if, in Fig. 72, $x\,o$, $d\,e$, are made respectively equal to $p\,c$, $p\,a$, we shall have a valve in which both the ports will be fully opened. It need hardly be observed that by the introduction, if required, of a rock shaft and lever as in Fig. 70, the greatest opening can be made to occur in either stroke, whether the valve be two-ported or three-ported, and whether the engine be direct-acting or back-acting; in what follows, therefore, unless the contrary be expressly mentioned, the connections of both crank and eccentric will be assumed as direct.

149. Now, let us suppose lead to be given, by advancing the eccentric to e at the beginning of the forward stroke, which will pull the valve forward from p to p'. After a half revolution, the eccentric being at e' for the return stroke, the valve will be found at b; but we have already seen that $p\,p'$ is less than $p\,b$; so that a given angular advance of the eccentric gives more lead on the return than on the forward stroke. And this is all; for the angular positions of the eccentric, at the beginning of each stroke and at the instants of closing the ports, being the same as when the eccentric rod was supposed to be infinite, it is clear that this closure must take place at the

same points, d in the forward and h in the return stroke. But a glance at Fig. 72 will show that if we extend the port $x\,O$ on the right as much as $p\,b$ exceeds $p\,p'$ in Fig. 71, the linear lead will be equalized; but since in order to close the port the eccentric must then move a little farther, the closure will take place still later in the forward stroke.

150. With a full-stroke valve, then, the introduction of the finite eccentric rod has the effect of making the linear lead and the port opening greater in one stroke than in the other. And the same results follow if the valve is arranged to cut off, as may also be seen from Fig. 71, regarding it simply as a diagram of the valve-movement. Thus, let e be the position of the eccentric at the beginning of the forward stroke; e' will be its position at the beginning of the return stroke, $e\,l'$ and $e'\,l$ the normal chords of action, which would give the equal port openings $c'\,w'$ and $a'\,v'$. But by the introduction of the finite rod, these openings become respectively $p'\,c$ and $b\,a$; the former being less, and the latter greater than $c'\,w'$, by as much as the hypothenuse ep', which is equal to $c\,c'$ or $a\,a'$, exceeds the base $w'\,p'$.

This is supposing that there is no lead; now let the eccentric be advanced from e to n, which would in the normal movement give the equal leads $w'\,d'$ on the forward, $v'\,h'$ on the return stroke.

The angular action of the rod changes these to $p'\,d$ and $b\,h$ respectively; but $p'\,d = w'\,d' + w'\,p' - d\,d'$; and $d\,d'$ being greater than $w'\,p'$, $p'\,d$ is less than $w'\,d'$, by an amount equal to the difference. On the other hand, $b\,h = v'\,h' + h'\,h - v'\,b$, or what is the same thing, $b\,h = w'\,d' + d\,d' - w'\,p'$; showing that the lead is just as much *greater* than its normal dimension on the return stroke as it is *less* on the forward stroke.

151. It is therefore plain that the cut-off can be equalized only at the expense of inequality of lead; and the process is illustrated in Fig. 81, which shows the movement of a valve arranged to cut off at half stroke in both directions, with no lead on the forward stroke. The piston movement being assumed as the same as that of the valve, the only difference between

this figure and Fig. 74, consists in the substitution of the finite radius, as $e x$, $f y$, $g v$, for the perpendiculars $e x'$, $f y'$, $g v'$, in determining the lead and the port openings.

152. If beside equalizing the port closure, it be stipulated that a certain linear lead be given on the forward stroke, it is no longer possible to assume the line of motion; because the *angular* lead will vary with the angular position of the rod, which depends both on the ratio of its length to the travel, and on the position of the eccentric.

Having ascertained from the diagram of the piston movement the angle through which the piston moves the crank in moving through the part of the forward stroke during which the admission is to continue, we find the full chord of action, the line of motion, and the position of the eccentric, by the process shown in Fig. 82.

153. Make $e\,O\,e'$ equal to the angle found as above; about e and e' as centres, with a radius equal to the length of the eccentric rod, describe the arcs $m\,n$, $p\,o$, intersecting each other at i. Draw $O\,r$, $O\,s$, $O\,t$ (any desired number of indefinite radiating lines), at pleasure, and, bisecting the portions $x\,x'$, $y\,y'$, etc., intercepted between the arcs $m\,n$ and $p\,o$, draw $i\,q$ through the points of bisection, g, h, k, etc., and, parallel to this curve, at a distance from it equal to half the given linear lead, draw the curves $u\,u'$, $v\,v'$, which will cut $m\,n$, $p\,o$, in b and a, through which two points draw L O M the line of motion; $e'f'$, perpendicular to L M, will be the chord of action, and e the initial position of the eccentric, for the forward stroke. Setting back $w\,l$ equal to $e\,b$, it is plain that, as shown, the lead on the forward stroke will be $a\,b$ as given, and the port opening will be $a\,l$. For the return stroke, the angle through which the crank moves before the time of closure is ascertained as before from the diagram of the piston movement, and laid off on Fig. 82 as $d\,O\,d'$, forward from d the extremity of the diameter $e\,d$; and from d, w', and d', with the radius $e\,b$, are set out on the line of motion the points b', l', a', giving $a'\,b'$ the lead, and $a'\,l'$ the port opening, for that stroke.

154. Fig. 81 represents an independent cut-off valve, like that shown in Fig. 74, which may be placed either on the back of the main valve or on the back of its valve-chest; in either case the eccentric may be placed at f instead of at e, at the beginning of the forward stroke, the edge x of the valve being in that case made to coincide at the same time with v of the port, which will be opened and closed at the same instants as now, only from the opposite edges, as will be seen by considering the action of the valve drawn in faint lines *under* the valve-seat.

155. The construction of the movement of a two-ported or a three-ported main valve, in which the points of cutting off and exhaust closure are equalized for the two strokes, taking into account the angular vibrations of both the main connecting rod and the eccentric rod, differs from that exhibited in Fig. 78, in these two respects: that the effect of a given linear lead in the forward stroke must be ascertained as in Fig. 82, and that the finite length of the eccentric rod must be made use of as in Fig. 81, in determining the lap, lead, and port openings, instead of the perpendiculars to L M, employed in the first-named diagram.

156. For the sake of illustration, we have in Fig. 83 drawn the movement of a valve arranged to fulfil the same conditions as the one shown in Fig. 78, viz., that the cut-off shall take place at five-eighths, and the exhaust closure at three-fourths, of each stroke, a definite linear lead to be given on the steam side for the forward stroke. The crank angles are therefore determined from Fig. 77: except that a' O l of that diagram is first laid out as e O f' of Fig. 83, and L M determined as in Fig. 82; thus fixing e, e', the initial positions of the eccentric for the forward and return strokes respectively; after which the angles are transferred from Fig. 77 to Fig. 82, e O h being made equal to a' O q, e' O g to c' O m, and e' O k to c' O q'.

After this, with the length of the eccentric rod, set off on L M from the points e, f', h, e', g, k, the points x, y, z, l, m, and n; a, b, c, being the extreme and mean points of the travel, determined with the same radius.

157. In order to make the action as clear as possible, the valve is drawn in its central position, with the steam edge for the forward stroke at b. When the eccentric has reached f, this edge will have advanced to y; and the eccentric in moving to e will carry it to x, giving the required lead $y\,x$; after which it will move to c, giving the port opening $y\,c$, and then return, reaching y again, and cutting off, when the eccentric reaches f', as required. The lap $u\,r$ is made equal to $b\,z$; so that r will coincide with u, closing the exhaust on the forward stroke, when the edge b of the valve is at z, at which time the eccentric is at h, as also called for by the conditions. But at the beginning of that stroke, b having gone beyond z to x, r must have passed beyond u, by the same distance $z\,x$, which is therefore the exhaust lead on that stroke, and $z\,c$ is the distance to which the exhaust port will be opened.

158. At the beginning of the return stroke, the eccentric is at e'; and if the steam edge of the valve be then at l, it must go to the right as far as a, and then back as far as m, when the eccentric being at g, the valve must meet the edge of the port in order to cut off as required, having still to go from m to b before reaching the central position. Therefore $m\,l$ is the steam lead, $m\,a$ the opening of the port, and $m\,b$ the lap on the steam side. If we suppose l to be the *exhaust* edge of the valve when the eccentric is at e', evidently it too must go to a, and in returning come back as far as n before meeting the edge of the port, in order to close the exhaust when the eccentric reaches k, as required. Consequently, $n\,a$ is the opening of the port, $n\,l$ the lead, and $n\,b$ is *minus lap;* the port being wider than half the travel, and the valve being obliged, as the result, to go beyond the central point to close it; a condition of things widely different from the normal one, but not astonishing when we consider the enormous lead.

159. The *actual* breadths of the ports may be assumed at pleasure ; but when in addition to the parts above specified, we make the steam lap $w\,O = b\,m$, and the minus exhaust lap $v\,s = b\,n$, and the distance $r\,t = O\,r + O\,u$, it is clear that all the conditions will be complied with in the action, $t\,v$ and $u\,p$ being arbitrary.

160. The equalization of the port closure in the case of the perforated valve, when the finite eccentric rod is introduced, is effected in the same manner, that is by using it as a radius, in setting off the positions of the port edges on the line of motion, from the eccentric positions ascertained from the diagram of the piston movement, instead of drawing perpendiculars to that line from those positions, as is done if the slotted crosshead connection be used for the valve motion.

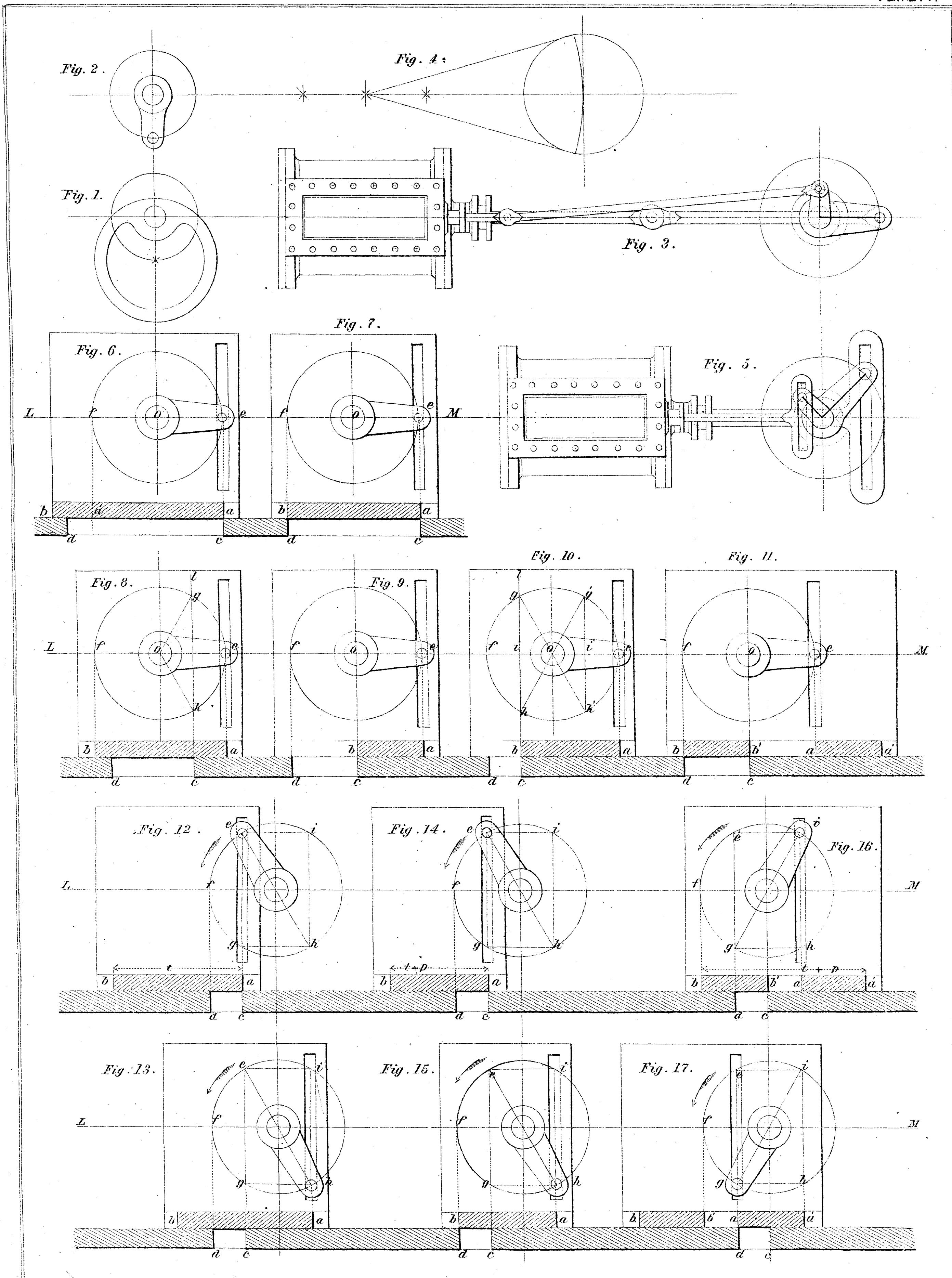
161. As an illustration, there is given in Fig. 84 a diagram of the movement of this valve, of which the conditions are the same as in the one shown in Fig. 79, viz.: that the valve without lead on the return stroke shall cut off at half stroke, in both directions. The angle $e\,O\,e'$, bisected at b', is made equal to $a'\,O\,l$ or $e\,O\,e'$ in Fig. 79, and from e and e' are determined the points d and n on L M, with a radius $e\,d$ equal to the given length of the eccentric rod. Drawing the diameter $e\,O\,f$, the angle $f\,O\,f'$ is made equal to $c'\,O\,m$ of Fig. 79, and from the point f' is determined the point r in the same manner as n and d were found; and since $f\,n = e'\,n$, $n\,r$ is the distance through which the eccentric moves the valve in traversing the arc $f\,f'$; and bisecting $n\,r$ at p, we have $n\,p$ for the port in the valve seat, and making the port $d\,s$ in the valve equal to it, we find $p\,s$ the lead on the forward stroke. Since d moves to the left as far as c, the valve-face $d\,u$ must be equal to $c\,p$, while it is only necessary that $v\,s = v\,n + n\,s = d\,a + d\,p = a\,p$.

162. Now, when it is required to introduce the final condition of a certain linear lead on the return stroke, we proceed as before by first determining the initial position of the eccentric for the forward stroke as though the same lead were to be given on that instead of the other; and, referring to Fig. 80, it is to be observed that neither the angle $e\,O\,e'$, through which the eccentric moves while the piston goes from the beginning of that stroke to the point of cutting off, nor the supplementary angle $e'\,O\,f$ described by the eccentric during the remainder of the stroke, are affected by the lead. And the chord $e'f$ of this supplementary angle has the same relation to the

line of motion L M, that the chord $e\,e'$ has in Fig. 82. Consequently, in Fig. 85, we make use of this chord $e'f$ and the given lead $l\,n$ to determine the line L M as in Fig. 82, thus ascertaining the positions f and e of the eccentric at the beginning of the return and forward strokes respectively ; after which the angle f O f' is set off, and the points d, n, r, ascertained as in Fig. 84, and as there, $n\,p$, one-half of $n\,r$, is the breadth of the port, and $p\,s$ the lead on the forward stroke.

163. Allusion has been made to the introduction of a rock shaft and lever, as a means of reversing the motion of the valve, by which the "forward" and the "return" strokes are virtually transposed, in so far as their relations to the matters herein discussed are concerned, as has already been intimated.

It may be said, that new irregularities will be thus introduced into the movement ; and this is true, so far as it goes. But they are of so insignificant a character, that in ordinary practice they may be disregarded altogether ; and even if they were not, they are not necessary results of such reversal of motion, as there is more than one way to get rid of them. Consequently we shall not enter upon a consideration of their nature or extent, our work ending, as it began, with an examination of the engine in its most simple form, with the fewest and most direct connections



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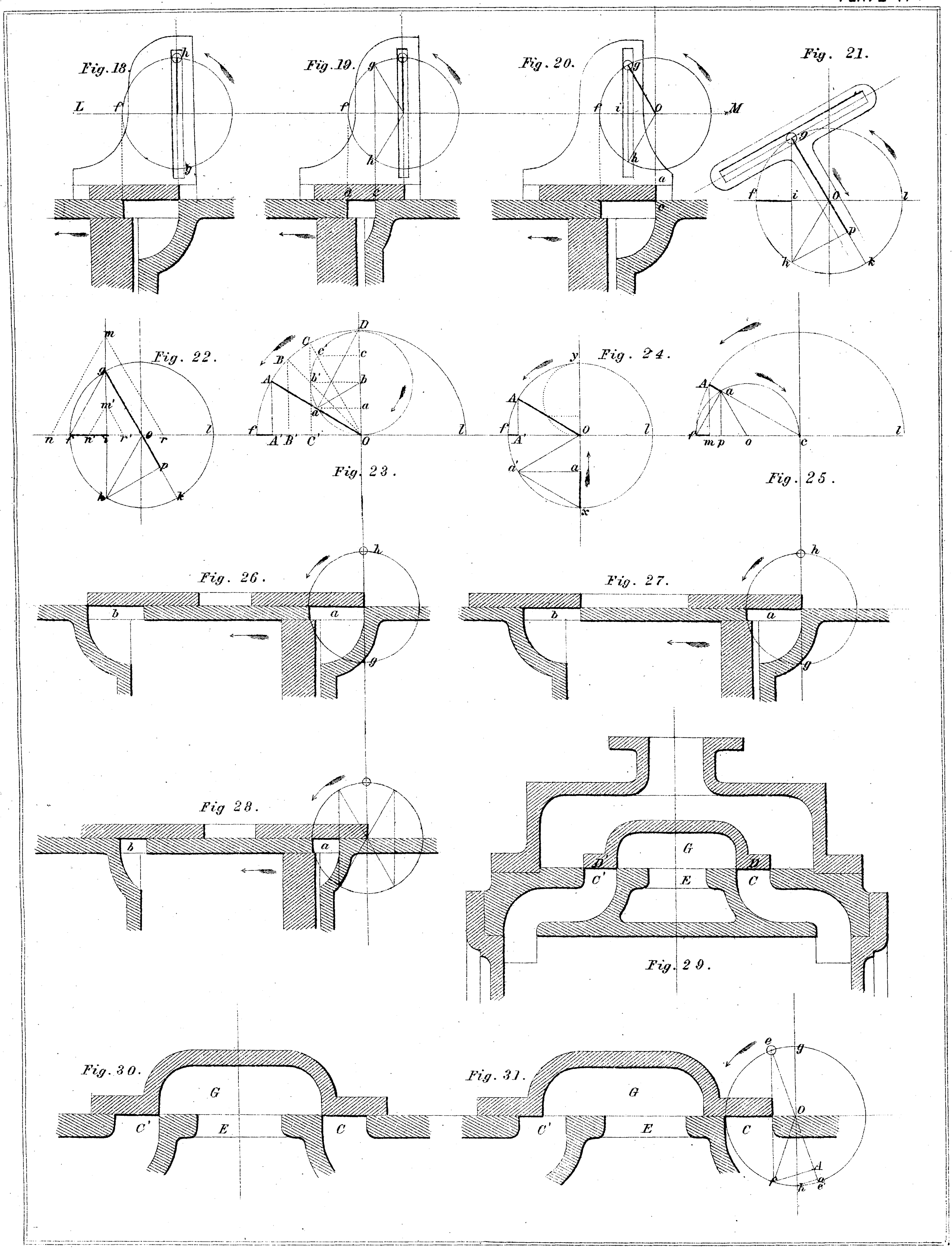
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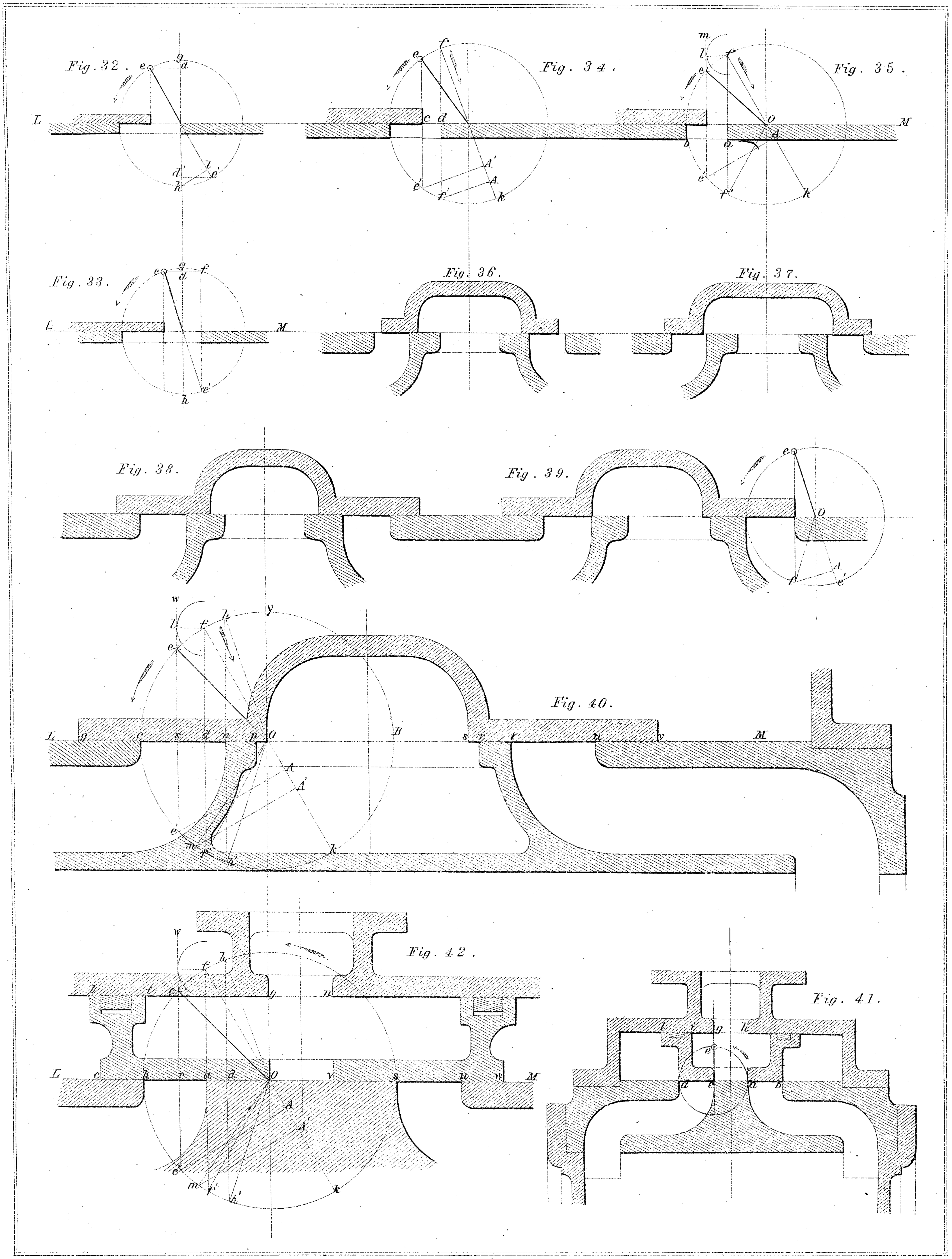
PLATE III.



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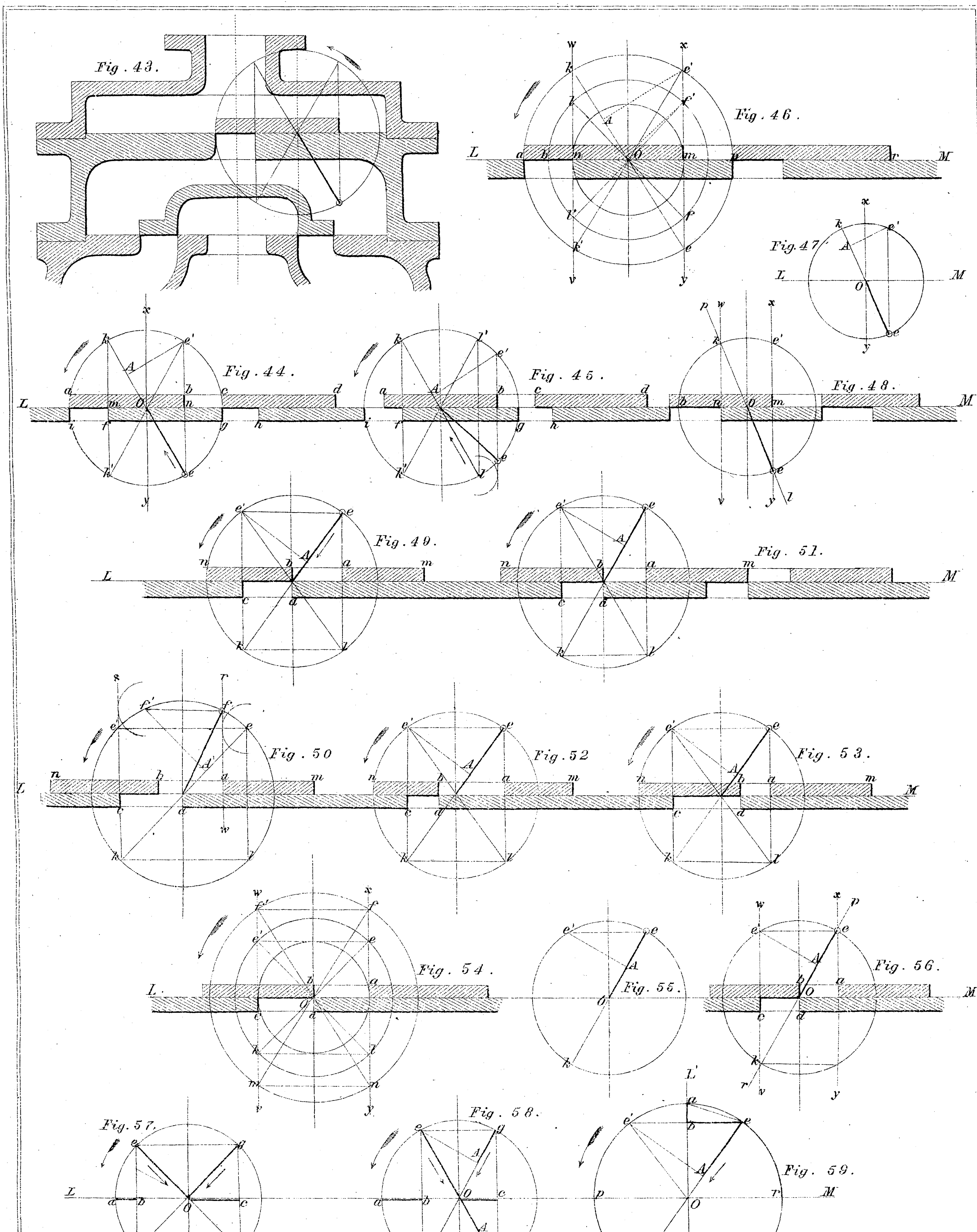
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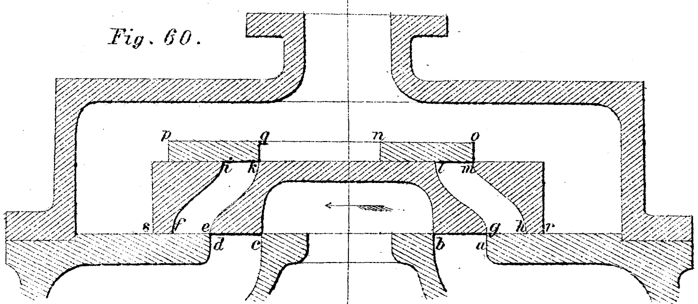

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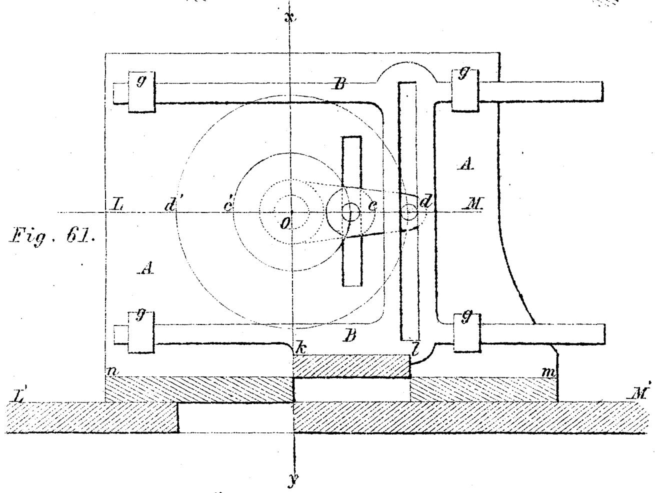

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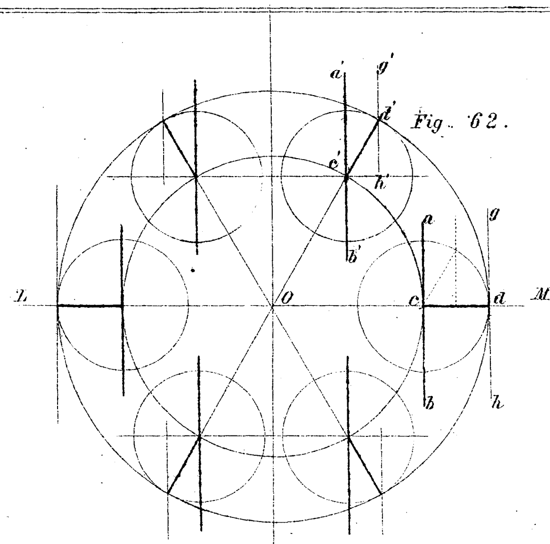

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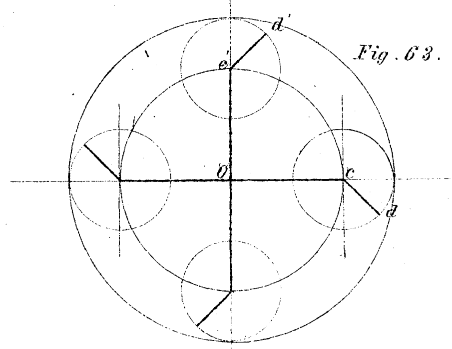

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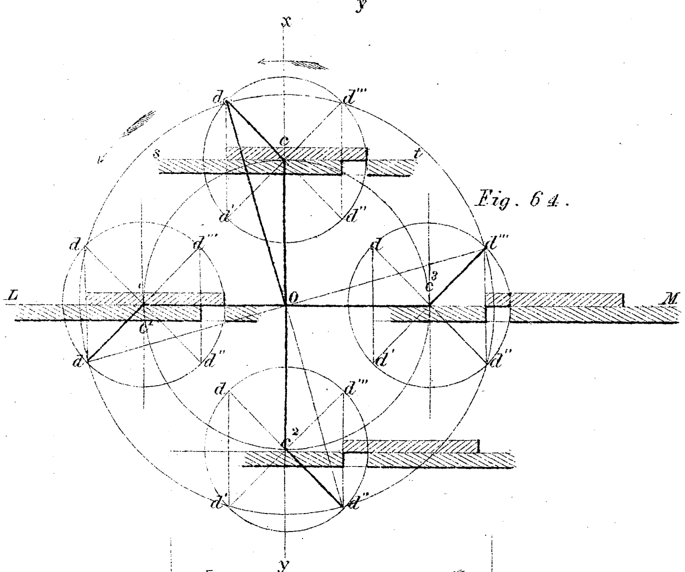

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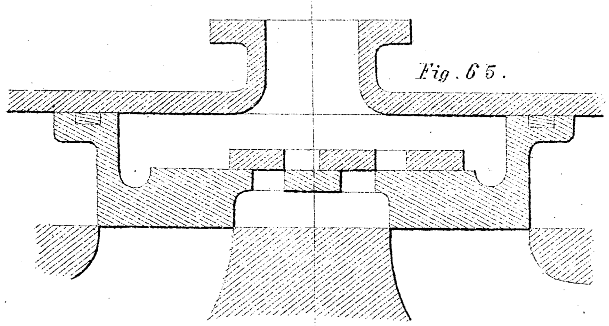

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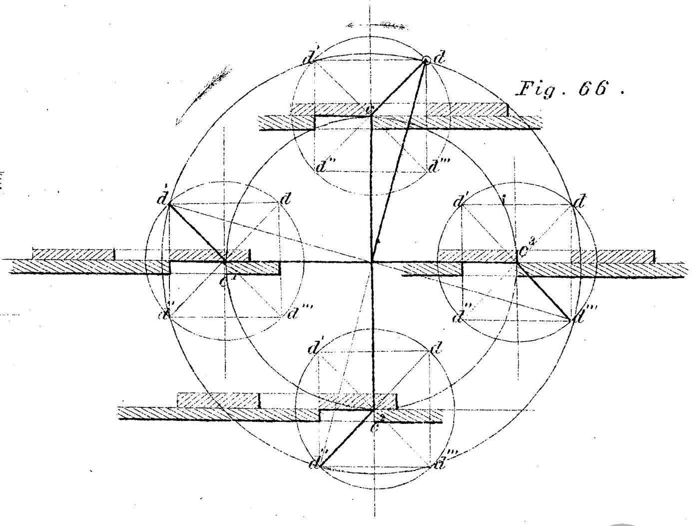

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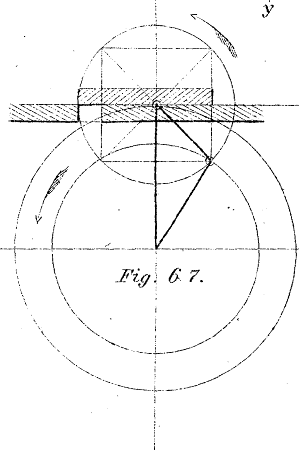

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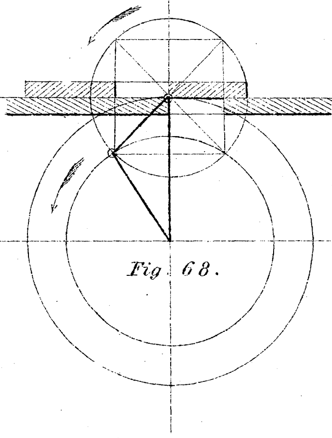

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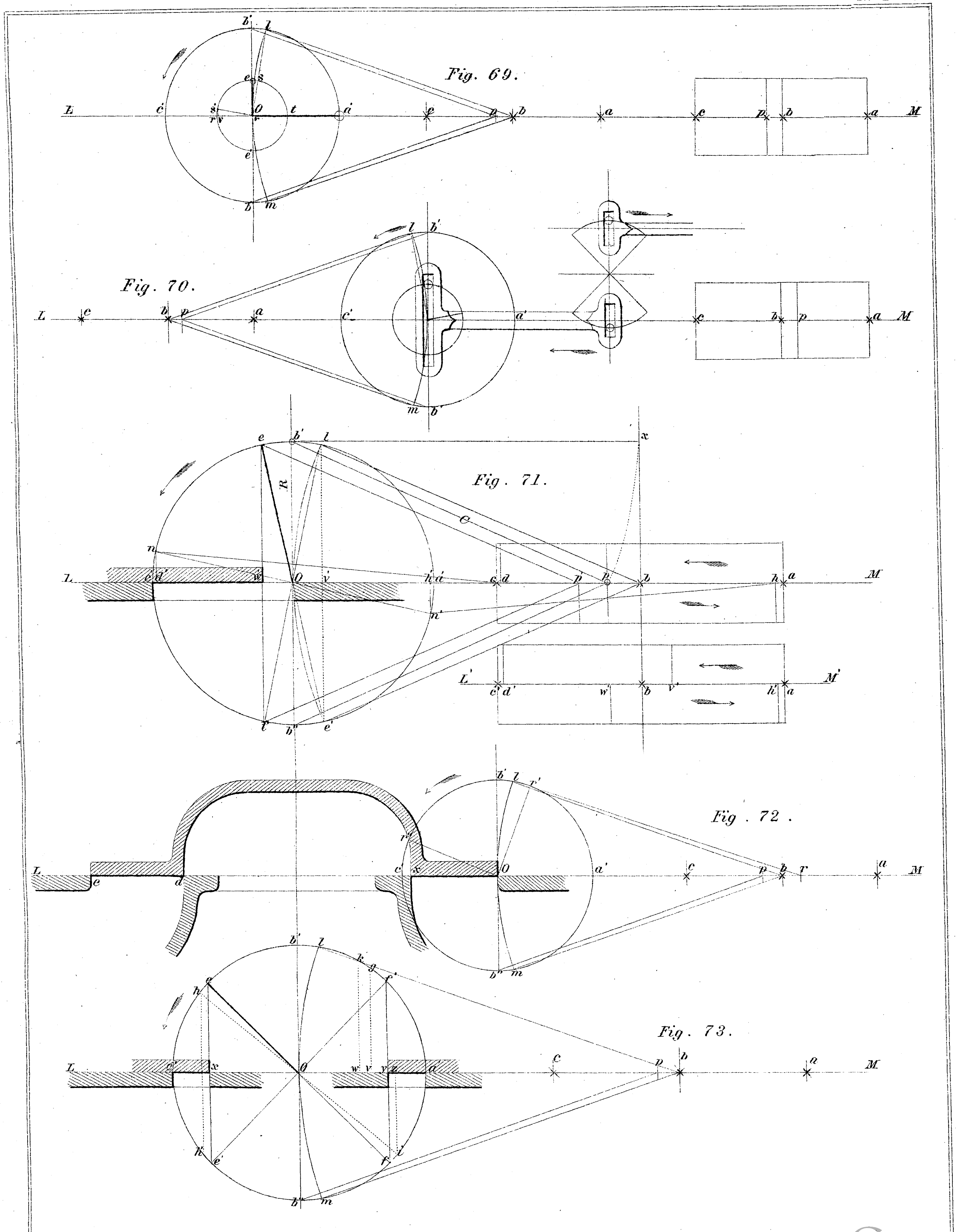

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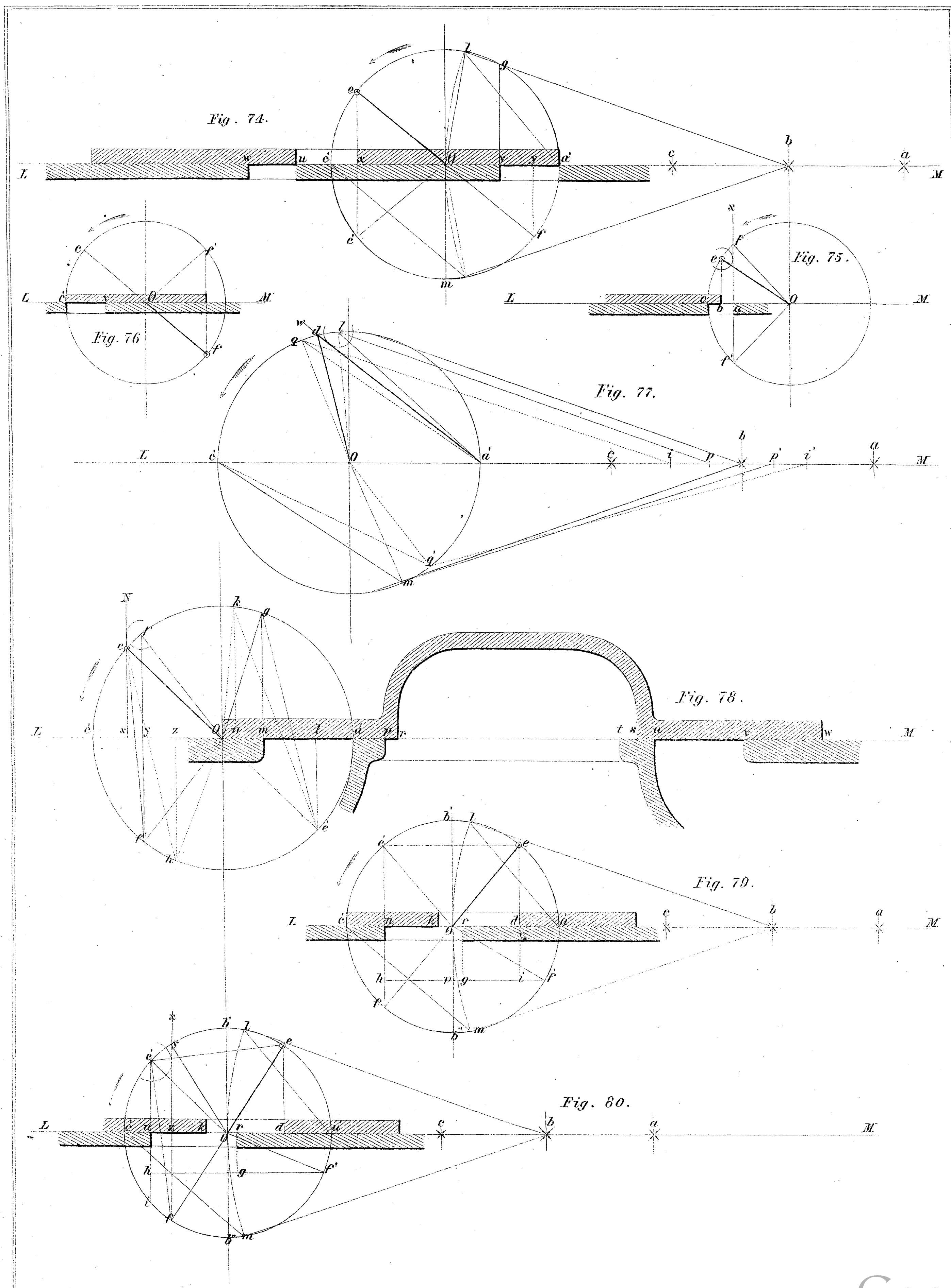

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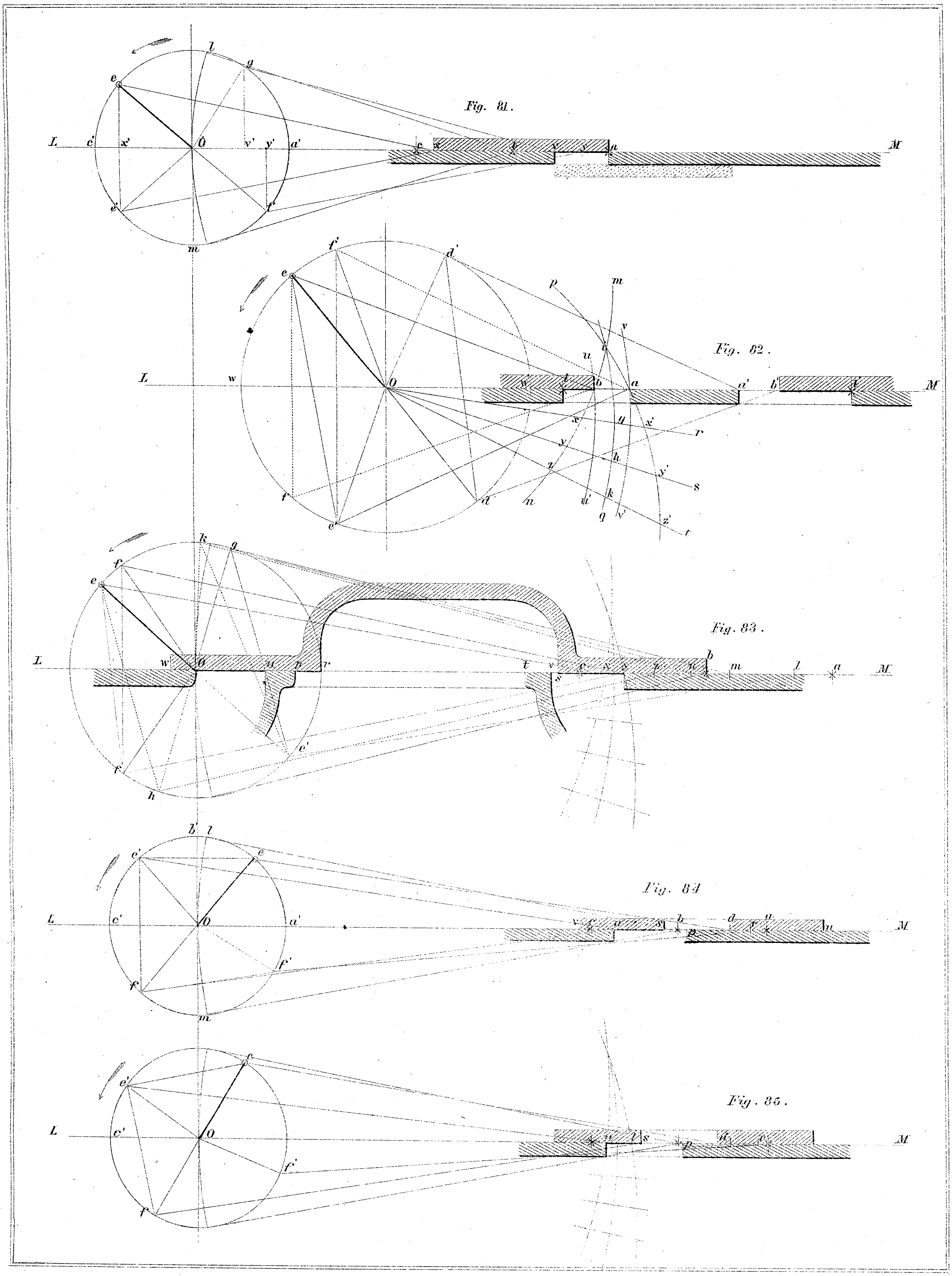
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Fig. 85.

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